

**INVESTIGATION OF EROSION WEAR IN METALLIC PIPE
BENDS**

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in
Mechanical Engineering**

**by
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March 2026**



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CERTIFICATE

This is to certify that the thesis entitled “**Investigation of Erosive Wear In Metallic Pipe Bends**” being submitted by **Bharat Singh Yadav**, Roll No.2K19/PhD/ME/22 to the Delhi Technological University, Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which has reached the requisite standard. The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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I, **Bharat Singh Yadav** hereby certify that the work which is being presented in the thesis entitled "**Investigation of Erosive Wear In Metallic Pipe Bends**" in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of **Mechanical Engineering**, Delhi Technological University is an authentic record of my own work carried out during the period from **01-August-2019** to **28 August 2025** under the supervision of **Prof. R. C. Singh** and **Prof. Rajiv Chaudhary**.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

For the transportation of powders from one place to another, pneumatic Conveying is widely used in industries. Pharmaceutical Industries, chemical industries, Ash Handling work, etc., had applications of Pneumatic Conveying. During conveying, due to the bombardment of particles on the bend inner surface for changing the direction of particles, bend erosion occurs, and bend puncture is a major problem in this system. To reduce the bending erosion, researchers are working on various factors that affect the bending erosion rate, like the hardness of particles, impingement angle, bend geometry, bend material, etc, but direct bombardment of particles at 30° angle is a severe bend erosion condition. Researchers are focused on inventing a device to change the mechanism to induce swirl flow before the bend so that bombardment of particles can be reduced, leading to a reduction in erosive wear. In this research, motor-operated Swirling devices and Auto swirl devices are used to reduce erosive wear in pipe bends. CFD numerical prediction and experiments are performed to find the efficiency of the auto swirl and motor-operated swirling device. A range of 20% to 50 % reduction in erosive wear with different parameters, like the mean effective particle size and rpm of the swirling device. The motor-operated swirling device was found to be more effective than the auto swirling device. With fine powders swirling, the device was found significantly effective with a 50% reduction in erosive wear. Experiment results validate the CFD numerical prediction with 10% more erosive wear in experimentation. A significant amount of reduction in bend erosion rate is the outcome of this research, but enhancement of design and experimentation can make these devices more effective. Auto Swirl Device can be more effective with different fan blade angle and this device is very energy efficient but, in this research, found less effective due to experimentation limitations.

Contents

CERTIFICATE	i
ACKNOWLEDGEMENT	ii
CANDIDATE’S DECLARATION	iv
CERTIFICATE BY THE SUPERVISOR(s)	v
ABSTRACT	vi
Contents	vii
LIST OF TABLES	xi
LIST OF FIGURES	xii
LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE	xvi
CHAPTER 1 INTRODUCTION	1
1.1 Motivation	1
1.2 Scope of the study	2
1.3 Structure of thesis	5
1.4 Delimitation	5
1.5 Theoretical background	6
1.6 Parameters of pneumatic conveying system	7
1.7 Types of pneumatic conveying system	8
1.7.1 Dilute phase (lean phase) conveying	8
1.7.2 Dense phase (thick phase) conveying	9
1.7.3 Semi-dense phase conveying	9
1.8 Wear in pipe bend	9
1.8.1 Parameters of pipe bend erosion	11
1.9 Factors affecting the erosion of pipe bend	12
1.9.1 Impact angle and surface material	12
1.9.2 Particle impact velocity and surface material	13

1.9.3 Particle hardness	14
1.9.4 Particle size	15
1.9.5 Solids loading ratio	16
1.9.6 Bend geometry	16
1.9.7 Surface finish	18
1.10 Benefits of pneumatic conveying system (PCS)	18
1.11 Application of pneumatic conveying system	19
1.12 Challenges of PCS	20
1.12.1 Challenges associated with materials	20
1.12.2 Challenges associated with the system	21
CHAPTER 2 LITERATURE REVIEW	23
2.1 Literature review	23
2.1.1 Parameters affecting the erosive wear of pipe bend	23
2.1.2 Swirling flow effect on wear of pipe bends erosion rate	26
2.1.3 Numerical investigation of erosive wear in pipe bend erosion rate	33
2.1.4 Erosion corrosion combined mechanism effect in pipe bend	40
2.1.5 Erosion of river bank bend	41
2.1.6 General erosion rate papers	41
2.2 Conclusions of literature review	47
2.3 Research gaps and motivation	47
2.4 Research objectives	48
CHAPTER 3 EXPERIMENTAL SETUP AND RESEARCH METHODOLOGY	49
3.1 Research methodology	49
3.2 Experimentation:	50
3.2.1 CFD numerical prediction	51
3.2.2 Simulation step of working	51
3.2.3 CFD governing equations:	55

3.2.4 Discrete phase modelling:	56
3.2.5 Uncertainties and errors in CFD	57
3.3 Experimentation setup.....	58
3.3.1 Steps followed in Experimental Setup: -	58
3.3.2 Experiment Setup for Swirling Device.....	58
3.3.3 Modification of test plant: -	62
3.3.4 Development of auto swirl device	63
3.3.5 Development of Auto Swirling Device with Swirl blades:	68
3.3.6 Sieve Analysis Apparatus:	69
3.3.7 Pin on Disc (POD) Tribometer	71
CHAPTER 4 EXPERIMENTAL RESULTS AND DISCUSSIONS	74
4.1 Experimental results.....	74
4.1.1 Results of pin on disc.....	74
4.1.2 Test on ultrasonic thickness gauge: -	78
4.1.3 Microstructure study: -	78
4.1.4 Macro examination: -	79
4.1.5 Hardness test: -	80
4.1.6 Spectroscopy results: -	80
4.2 Bend erosion experimental setup results	80
4.2.1 Operating parameters for experimentation:	84
4.2.2 Experiments Results:	84
4.3 CFD Results	86
4.3.1 CFD Numerical Prediction Swirling Device Motor Operated: -	86
4.3.2 Validation of CFD	88
4.3.3 Grid Independence Test:.....	89
4.3.4 CFD Results for 90° bend.....	90
4.3.5 Motor operated Swirling Device Used at different Bend Angles: -	97

4.3.6 CFD results of auto swirling device with blades: -	103
4.4 Cases taken in CFD results of Auto Swirler:	104
4.4.1 CFD results at inlet velocity 23 m/s	104
4.4.2 CFD results of auto swirler at 30m/sec	106
4.4.3 CFD results of auto swirler at velocity 35m/s	107
4.5 Auto swirler results comparision.....	108
4.6 Experimental Results of swirling Device:.....	109
CHAPTER 5 CONCLUSIONS AND FUTURE SCOPE.....	111
5.1 CONCLUSIONS	111
5.2 RECOMMENDATIONS FOR FUTURE WORK.....	113
Appendix 1	121
RESEARCH PUBLICATIONS:.....	123

LIST OF TABLES

Table 2.1 Parameter affecting erosion of pipe bend	24
Table 2.2 Swirl flow in pipe bend.....	29
Table 2.3 Mathematical modeling of pipe bend erosion.....	33
Table 2.4 Literature review of erosion corrosion combine effect.....	40
Table 2.5 Erosion Mechanism in river bend.....	41
Table 4.1 Wear test parameters and their levels	74
Table 4.2 Loss of Thickness due to erosion on Ultra Sonic thickness gauge.....	78
Table 4.3 Elemental results of failed pipe bend.....	80
Table 4.4 Fresh silica sand particle size.....	81
Table 4.5 silica sand particle size after 5 run.....	82
Table 4.6 silica sand particle sizes without swirling device after 10 run	83
Table 4.7 Operational parameters for swirling experiments.....	84
Table 4.8 Experimental result	85
Table 4.9 Operating Parameters for CFD modelling	88
Table 4.10 CFD Results.....	96
Table 4.11 CFD Results at different bend angles	102
Table 4.12 Bend erosion and blade erosion results of auto swirler	108
Table 4.13 Experimental results of motor operated and auto swirl device.....	109

LIST OF FIGURES

Fig. 1.1 Pipe bends with replaceable backs (www.claytonequip.com)	2
Fig. 1.2 Pipe bend of rectangular cross section with replaceable back(www.lorenz.ca)....	3
Fig. 1.3 Pipe bend with shallow depression (www.pelletroncorp.com)	3
Fig. 1.4 Bends with replaceable and interchangeable segments (www.sunnysteel.com)...	4
Fig. 1.5 Strengthening of bend for wear reduction [5]	4
Fig. 1.6 Strengthening of pipe bend by concrete reinforcement [4]	4
Fig. 1.7 Reduction of bend wear by manipulating the impact angle	5
Fig. 1.8 Schematic diagram of a laboratory pneumatic conveying system [1]	6
Fig. 1.9 Closer view of punctured pipe bend	10
Fig. 1.10 Enlarged view of pipe bend having hole and erosion pattern.....	10
Fig. 1.11 Probable erosion mechanisms [2].....	11
Fig. 1.12 Change in erosion rate with different impact angle [1]	13
Fig. 1.13 Difference in erosion rate at different particle velocity [1]	14
Fig. 1.14 Effect of particle hardness on the specific erosion of bends [1].....	14
Fig. 1.15 Effect of size at different velocities of particle on erosion [1]	16
Fig. 1.16 Effect of solids loading ratio on the bends conveying capacity [1].....	16
Fig. 1.17 Impact of geometry on the bend's specific erosion wear [1]	17
Fig. 1.18 Effect of bend geometry on impact angle of particles [1]	18
Fig. 2.1 Swirl mechanism [12].....	26
Fig. 2.2 Swirling by Robinson [13]	27
Fig. 2.3 Patent by Yuille [14].....	27
Fig. 2.4 Patent for transporting slurries by Wolfe [15].....	28
Fig. 2.5 Patent by Garbo [16].....	28
Fig. 2.6 Swirly flow boiler tube	43
Fig. 2.7 The upstream swirl (right) effect on the particle dispersal in a bend [11].....	43
Fig. 2.8 Particle motion in swirling	44
Fig. 3.1 Research methodology	50
Fig. 3.2 Systematic Diagram of Pilot Plant [44].....	59
Fig. 3.3 plant Photograph [44]	60
Fig. 3.4 Storage Hopper with three load cells 120 degrees apart [44].....	60
Fig. 3.5 Root Blower [44].....	61

Fig. 3.6 Pressure gauges [44]	61
Fig. 3.7 New loop for modified plant for swirling device [44]	62
Fig. 3.8 Motor operated Swirling Device [44]	62
Fig. 3.9 Conveying Hopper With Flow control attachment	63
Fig. 3.10 Root blower	63
Fig. 3.11 Bends of auto swirl device	64
Fig. 3.12 Alloy steel EN24 metal Labyrinth seal	64
Fig. 3.13 Labrynth Seal drawings	65
Fig. 3.14 3D printer STL file of male and female part of Labyrinth seal	66
Fig. 3.15 Auto Swirler Drawing	67
Fig. 3.16 Auto Swirler STL file and final 3D Printed file	67
Fig. 3.17 Autoswirler assembly	68
Fig. 3.18 Weighing Machine measured Bend weight	68
Fig. 3.19 Bend erosion apparatus	69
Fig. 3.20 Different types of sieves	70
Fig. 3.21 Sizes of sieve	70
Fig. 3.22 Sieve Analysis Apparatus	71
Fig. 3.23 Pin on Disc	72
Fig. 3.24 Specimen Sample size on Pin on Disc Test Rig [56]	72
Fig. 4.1 POD wear impressions on emery 80	75
Fig. 4.2 POD wear impressions on emery 100	75
Fig. 4.3 POD wear impressions on emery 120	76
Fig. 4.4 Plots of means	76
Fig. 4.5 Standard Deviation Plots	77
Fig. 4.6 Main Effects Plot of SN ratios	77
Fig. 4.7 Microscopic View of Bend Punctured section	79
Fig. 4.8 Macroscopic examination specimen	79
Fig. 4.9 Fresh silica sand without swirling	81
Fig. 4.10 silica sand particle size without swirling device after 5 run	82
Fig. 4.11 silica sand particle sizes without swirling device after 10 run	83
Fig. 4.12 Effect of swirling on bend	85
Fig. 4.13 Experimental Data Graph	86
Fig. 4.14 Bend without Motor Operated Swirler	87
Fig. 4.15 Bend with Motor operated swirler	87

Fig. 4.16 Model Validation	89
Fig. 4.17 Grid Independence Test.....	89
Fig. 4.18 Meshing Details of CFD model.....	89
Fig. 4.19 Erosion rate and velocity contour at 200 μm particle size without swirling device	90
Fig. 4.20 Erosion rate and velocity contour at 250 μm particle size without swirling device	90
Fig. 4.21 Erosion rate and velocity contour at 250 μm particle size without swirling device	91
Fig. 4.22. Erosion rate and velocity contour at 220 μm particle size with swirling device(35rpm).....	91
Fig. 4.23 Erosion rate and velocity contour at 250 μm particle size with swirling device(35rpm).....	92
Fig. 4.24 Erosion rate and velocity contour at 300 μm particle size with swirling device(35rpm).....	92
Fig. 4.25 Erosion rate and velocity contour at 200 μm mep with swirling device (70rpm)	93
Fig. 4.26 Erosion rate and velocity contour at 250 μm mep with swirling device(70rpm)	93
Fig. 4.27 Erosion rate and velocity contour at 300 μm mep with swirling device(70rpm)	94
Fig. 4.28 Erosion rate and velocity contour at mep 200 μm with swirling device(100rpm)	94
Fig. 4.29 Erosion and velocity contour at mep 250 μm with swirling device(100rpm)...	95
Fig. 4.30 Erosion and velocity contour at mep 300 μm particle size with swirling device(100rpm).....	95
Fig. 4.31 Erosion graph at different bend conditions.....	97
Fig. 4.32 Different bend angles.....	97
Fig. 4.33 Erosion and velocity contour at 200 μm particle size without swirling device	98
Fig. 4.34 Erosion and velocity contour at 200 μm particle size without swirling device	98
Fig. 4.35 Erosion rate and velocity contour at 200 μm particle size with swirling device	99
Fig. 4.36 Erosion rate and velocity contour at 200 μm particle size without swirling device	99

Fig. 4.37 Erosion rate and velocity contour at 200 μm particle size with swirling device	100
Fig. 4.38 Erosion rate and velocity contour at 200 μm particle size with swirling device	100
Fig. 4.39 Erosion rate and velocity contour at 200 μm particle size with swirling device	101
Fig. 4.40 Erosion rate and velocity contour at 200 μm particle size with swirling device(100rpm).....	101
Fig. 4.41 Erosion rate graph at different bend conditions.....	102
Fig. 4.42 Isometric view of CFD model with Auto swirl blades.....	103
Fig. 4.43 Drawing of Auto Swirling Device.....	103
Fig. 4.44 Drawing of Swirling Blades	104
Fig. 4.45 Velocity and pressure contour for auto swirler at air inlet velocity 23m/s.....	104
Fig. 4.46 Erosion rate Contour for auto swirler at air inlet velocity 23m/Erosion	105
Fig. 4.47 erosion of blades for auto swirler at air inlet velocity 23m/s	105
Fig. 4.48 Velocity and pressure contour results at 30m/s	106
Fig. 4.49 Blade erosion contour at velocity 30m/sec.....	106
Fig. 4.50 Velocity and pressure contour at 35m/sec	107
Fig. 4.51 Blade erosion at 35m/s	107
Fig. 4.52 Comparison of experimental results of auto swirler.....	108
Fig. 4.53 Comparison of bend erosion rate.....	109

LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

Symbol/ Abbreviation	Nomenclature	Units
PCS	Pneumatic Conveying System	N.A.
BER	Bend Erosion Rate	mm/year & (kg/m ² s)
SLR	Solid Loading Ratio	Dimensionless
AF	Plasma Electrolytic Oxidation	N.A.
CFD	Computational Fluid Dynamics	N.A.
DPR	Discrete Phase modelling	N.A.
POD	Pin on Disc	N.A.
U. S.	United State	N.A.
AFPC	Axial Flow Pneumatic Conveying	N.A.
RANS	Reynolds-averaged Navier–Stokes equations	N.A.
k	Tubulent kinetic energy	J/Kg
ω	Specific dissipation rate	1/s
F1	Blending Function	N.A.
S	Strain Rate	1/s
P _k	Production of turbulent kinetic energy	J/Kg

CHAPTER 1

INTRODUCTION

This chapter covers motivation for this research work, scope of study, background, erosive wear in pipe bend, factors affecting erosive wear in pipe bend, benefits of pneumatic conveying system(PCS). Application of PCS and challenges of PCS. Pneumatic conveying system and powder transportation from one place to another place through pneumatic conveying are described in this chapter.

1.1 Motivation

First Law of thermodynamics emphasizes that Energy is neither created nor destroyed but it can be converted alternate form of energy. Energy transformation had wide range application in every field of engineering and human science. Energy utilization is good for human being but its wastage can create global warming. Energy studies are the main focus for the researchers of various field because it is the source of life on our earth. Energy is productive as well as non-productive for our applications. Non-productive energy can be utilized by various research apparatus and perform useful application in engineering applications.

In this era of industrialization pneumatic conveying was implemented from the end of 19th century to this 21st century had application in research from more than 200 years. It is the best method of transportation in various industries like pharmaceutical, Ash handling, cattle food etc. Bend erosion in pneumatic conveying system is destructive effect of energy transformation. Various researchers and scientists want to reduce this.

Bend erosion has wide scope in industrial pipes (oil and gas, processing)

Economic Impact and Maintenance Costs: One of the main causes of material degradation is pipeline erosion, especially around bends. For high-pressure systems, predicting erosion rates helps save downtime, prevent premature failures, and improve maintenance schedules.

Safety and Integrity Management: High-velocity hits at bend elbows pose a danger to structural integrity due to sand production in oil and gas or abrasive slurries in processing. Creating predictive models to stop catastrophic pipe breakdowns is made possible with a Complex Fluid Dynamics and Modelling: Advanced Computational Fluid Dynamics

(CFD) is necessary to comprehend how solid particle impact angle, velocity, and concentration affect material removal. Enhancing wear models and multi-phase flow (such as gas-solid or liquid-solid) are common research topics. This research is purely practical and had scope of industry academic partnership.

1.2 Scope of the study

Attempts have been done in past to design and develop relatively long life bends for pneumatic conveying pipeline system. Fig, 1.1 - 1.7 demonstrate various designs of bends for having definite advantages in reduction of wear of bends over the conventional design of bend.

In Fig. 1.1 two bends 90° and 120° angle with replaceable back which can easily assemble and dissemble with the help of nut and bolt. These bends are the solutions of erosion as bend puncture then only back can be replaced can reduce bend changing time as well as increase productivity.



Fig. 1.1 Pipe bends with replaceable backs (www.claytonequip.com)

In Fig. 1.2, a long radius bend with a rectangular cross section is shown in this bend we can easily replace it with a multi-nut bolt assembly shown in Fig. 1.2. It is a very good bend which can be easily used for pneumatic conveying. These replaceable backs are very good and improves the efficiency of pneumatic conveying systems.



Fig. 1.2 Pipe bend of rectangular cross section with replaceable back(www.lorenz.ca)

In Fig. 1.3 Patented Pipe bend with shallow depression is shown, shallow depression increase area at bend surface which reduce the bend erosion rate. Shallow bend had fluids dynamics and structural behaviors that occur when fluids travel through curves with small radius of curvature. These bends induce significant energy losses, flow separation and complex vortex formation.

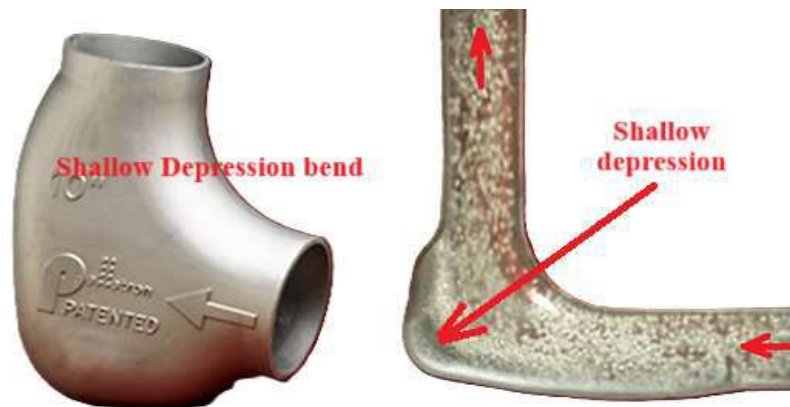


Fig. 1.3 Pipe bend with shallow depression (www.pelletroncorp.com)

In Fig. 1.4, Pipe line with interchangeable backup is shown, when one bend puncture then In pneumatic conveying systems redundancy in the system can be maintained by backup bend is attached in pipeline which save breakdown time as well as increase efficiency and productivity.



Fig. 1.4 Bends with replaceable and interchangeable segments (www.sunnysteel.com)

In Fig. 1.5, the Pipe bend is strengthened by a welded plate. This welded plate will increase the bend life. At the time of eroded material depth increases can make bend robust for some significant time.

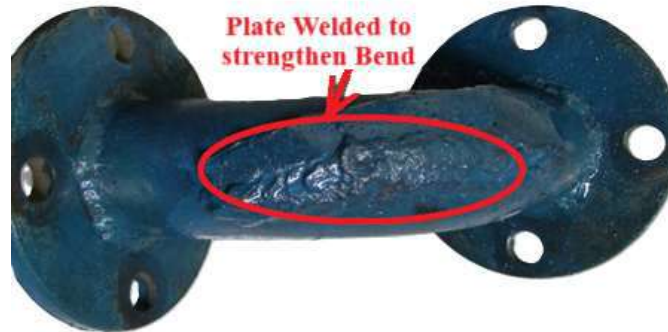


Fig. 1.5 Strengthening of bend for wear reduction [5]

In Fig. 1.6, Pipe bend is strengthened by welding plate was shown. This welded plate will increase bend life. The concrete make robust system but has contamination problems.



Fig. 1.6 Strengthening of pipe bend by concrete reinforcement [4]

Inner side of Pipe bend is welded with corrugated arrangement shown in Fig. 1.7. This corrugated arrangement manipulates the impact angle and enhance the life of bends and reduces the significant amount of erosion rate.



Fig. 1.7 Reduction of bend wear by manipulating the impact angle

Positive results achieved with different designs of pipe bends in the field of pneumatic conveying pipeline systems encourage for exploring further the innovative designs of bends for drastic reduction in the erosive wear and consequently longer life of bends. Thus, there is strong scope for study to design and develop smarter pipe bends for longer life by manipulating the impact velocity of particles at the bend for reducing the bend wear.

1.3 Structure of thesis

The structure of this thesis comprises several chapters described below:

Chapter 1: Introduction

Chapter 2: Literature review

Chapter 3: Experimental setup and research methodology

Chapter 4: Experimental results and discussions

Chapter 5: Conclusions and future scope

1.4 Delimitation

It is important to remember that certain subject areas could not be covered due to time and scope limits. Because some subject areas will require more time and resources to complete within the parameters of this research endeavor, the delimitation is discussed here. Due to the unavailability of a pneumatic conveying plant, a small setup was used to perform experiments. Auto swirler fan blade was fabricated by 3D printer with PLA material due to critical geometry machining issues. In Auto swirling Silica sand micro particle stuck in Auto and rpm of self-powered swirler reported approximately Zero. Enhance design and use of higher compressor pressure can resolve this issue of experimentation. Due to unavailability of resources calibration of length of swirler was not performed. Due to time

and resources cause delimitation in this research. CFD convergence problems at smaller mean effective particle sizes are limiting results.

1.5 Theoretical background

Pneumatic conveying is commonly used to transfer a variety of dry powders and granular solid particles via pipelines with a large gas/air pressure gradient and changing the direction of flow by bends. Businesses, regions, and companies use it extensively to transport commodities across short or long distances. In addition to lowering dust, it offers flexibility in pipeline layout. Fig. 1.8 shows the schematic diagram with labelling of a laboratory pneumatic conveying system, illustrating the flexibility of pipe routing with bends.

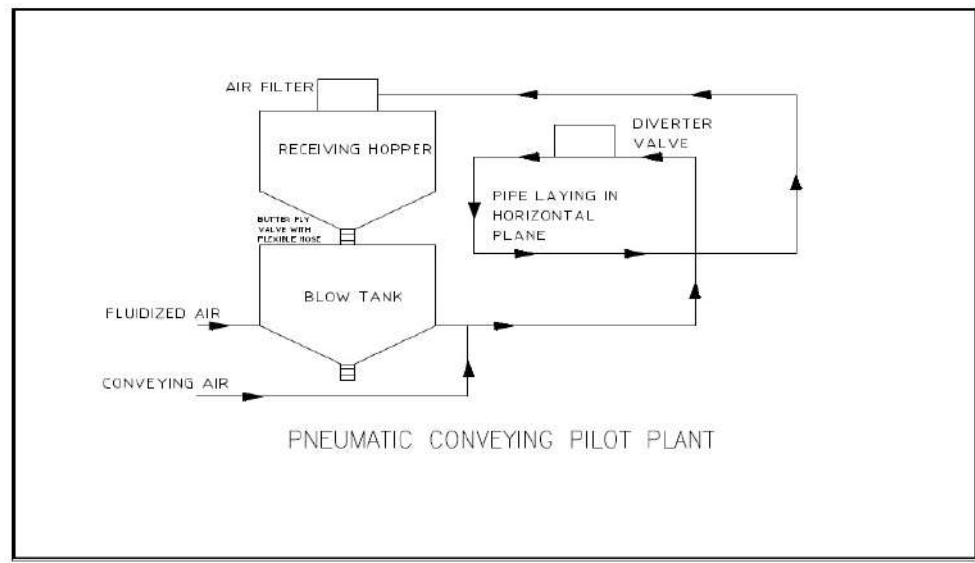


Fig. 1.8 Schematic diagram of a laboratory pneumatic conveying system [1]

It is significant to note that diluted phase pneumatic conveying accounts for almost 80% of industry. Conveying systems that require comparatively higher air or gas flow to maintain high particle velocity in order to prevent dry powder or material from choking in pipelines. Higher particle velocity, however, is observed to enhance particle attrition and, consequently, the bend erosion wear rate in pipes in many pneumatic conveying applications. Furthermore, bends are the cause of a number of PCS issues, including bend erosive wear rate, material choking, high pressure loss, and mean effective particle size degradation. It is said here that choosing the right bend materials to extend the life of bends is one method to lower the bend erosive wear rate of pipe bends. Another smart strategy, though, is to build various bends so that the impingement angle of particle impact at the

bends varies. This can lower the rate of bend erosion and material clogging in pipelines and pipe bends, respectively.

Nearly 80% of pneumatic material conveying in industrial applications is carried out in the diluted phase, where a large volume of air or gas is employed to keep the particles moving at high velocity and dodges the pipeline blockages. Nevertheless, in many situations, these high velocities of air/gas can lead to increased particle breakage and faster wear of the conveying lines. Bends in the pipeline are particularly prone to numerous challenges such as high pressure losses, particle separation, product damage, roping, erosion etc. Use of wear-resistant materials for bends may help in extending their operational life. Another effective tactics is to modify the designs of bend so that particles strike the bend surface at more favorable angles, which can reduce both erosion and the chance of blockages in bends and the overall pipeline systems.

1.6 Parameters of pneumatic conveying system

Key parameters for a pneumatic conveying system, especially concerning solid loading ratio (SLR), include the solids loading ratio (mass rate of solids to mass rate of air), conveying velocity, operating pressure, air/solid mover type (e.g., blower, fan), conveying rate (throughput), and conveying distance. The SLR value indicates the concentration of material in the air stream and influences whether the system operates in dilute or dense phase. High SLR typically leads to higher pressure drops and can suggest denser flow, while lower SLR is characteristic of dilute phase flow.

Solids loading ratio (SLR) - The SLR (also called phase density) is the ratio of the mass flow rate of the conveyed material to the mass flow rate of the conveying air. It is a dimensionless value, for instance, an SLR of 10 means 10 kg of solid material is conveyed for every 1 kg of air. A low SLR (e.g., 1 to 10) is typical of dilute phase conveying, where solids are suspended in the air stream, while higher values can indicate a denser, more plug-like, or moving bed flow, particularly in dense phase conveying.

Conveying velocity-This is the speed of the material and air in the pipeline. Lower velocities can support higher solids loading ratios and dense phase flows, while higher velocities are necessary for dilute phase to keep solids suspended.

Operating pressure- Systems operate at positive pressure, vacuum (negative pressure), or a combination of both. Higher pressures generally allow for higher solids loading ratios.

Air Mover: The device that creates the airflow, such as a blower (positive displacement or roots-type), fan, or exhauster.

Conveying rate- The total amount of material being transported over a given period (e.g., tons per hour).

Conveying distance- The length of the pipeline. Longer distances can significantly affect pressure drop and require careful parameter selection to maintain efficient transport, particularly at high SLR values.

Material properties- The physical characteristics of the solid material, such as particle size, density, and permeability, are critical for determining the appropriate parameters, especially the minimum conveying air velocity needed to fluidize the material effectively.

1.7 Types of pneumatic conveying system

Pneumatic conveying systems are primarily classified into two main types: Dilute Phase (or Lean Phase) and Dense Phase, with a third category, Semi-Dense Phase, often included. Dilute phase systems use a high volume of air to suspend particles in a fast-moving stream, ideal for non-abrasive, non-fragile materials over short to medium distances. Dense phase systems, using lower air velocity and higher material concentrations, move materials in batches or slugs, making them suitable for abrasive or fragile materials and longer distances.

1.7.1 Dilute phase (lean phase) conveying

Particles are fully suspended in a high-velocity air stream, with a low particle-to-air ratio. Ideal for: Non-abrasive, non-fragile, free-flowing materials. Requires high superficial air velocities to keep particles suspended. Consumes significant energy. It can cause wear and tear on pipelines due to particle abrasion. Not suitable for easily damaged or fragile materials. Applications: Transferring powders, granules, and other bulk solids in many industries. 5:1 and 15:1 (material to air) is the solids loading ratio (SLR). Particles are suspended by high air velocities (18 m/s to 35 m/s). It uses modest conveying pressure (up to than 1 bar).

1.7.2 Dense phase (thick phase) conveying

Materials are moved in "batches" or "slugs" within the pipe, with lower air velocity and a high material-to-air ratio. This type is used for Abrasive, fragile, or heat-sensitive materials that can be damaged or cause damage if conveyed at high speeds.

Uses medium to high pressures to move materials. Lower air velocity reduces material degradation and pipeline wear. Can handle larger throughputs and longer distances. Material is moved in a more concentrated flow using high conveying pressures (over 1 bar) and low air velocities (3 m/s to 14 m/s). very high, usually greater than 30:1 (material to air). Application in Transporting materials like cement, plastic pellets, and other fragile or abrasive bulk solids.

1.7.3 Semi-dense phase conveying

This method operates between dilute and dense phase conditions, often used when a material is too dense for dilute phase but not dense enough for a full slug-type dense phase system. Materials that can be transported as a mixture of suspended particles and some bed-like movement can involve moving in a moving strand or flow where material forms a bed at the pipe's bottom. Some specialized applications where material properties fall between those of dilute and dense phase systems. The choice between these types depends on several factors are particle size, abrasiveness, fragility, and density all play a role.

Application Requirements: Throughput, conveying distance, and the number of sources and destinations influence the system design. Dilute phase systems generally consume more energy than dense phase systems.

1.8 Wear in pipe bend

The material particles in pneumatically transporting pipelines can freely roll, slide, and contact any area of the pipeline, including bends. As a result, the intricate process of removing material from the pipe bend's surface is in danger. This is known as wear of the material on the bend's wall surface. As seen in Figs. 1.9 and 1.10, unembellished wear may cause a puncture in the bend's wall. Excessive material loss could happen in the vicinity of the puncture. In order to reduce failures and increase the useful service life of pneumatically conveying pipelines, it is imperative to comprehend the mechanism of wear in the punctured zone of pipe bends.

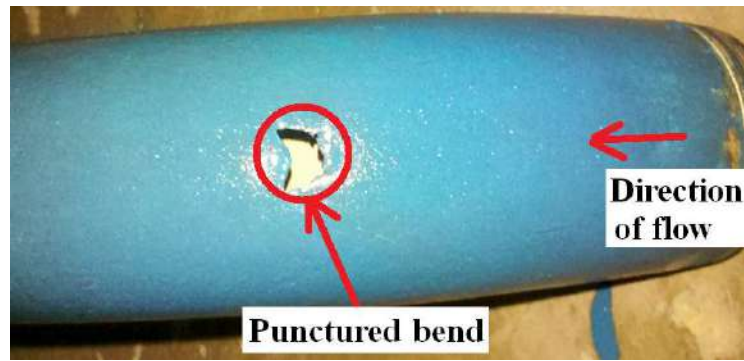


Fig. 1.9 Closer view of punctured pipe bend

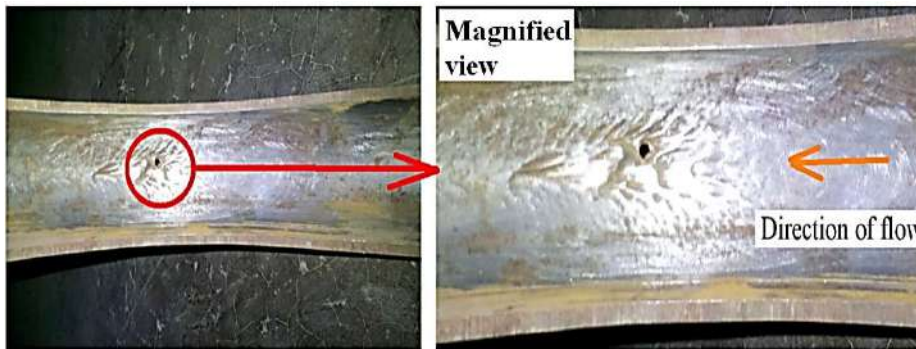


Fig. 1.10 Enlarged view of pipe bend having hole and erosion pattern

It is worth noting here that erosive wear of bend is triggered by the impact of powder/granular particles of conveying materials over the surface of bend materials. Erosive wear encompasses numerous wear mechanisms which are principally controlled by the nature of the particle material, angle of impingement, velocity of impact, size of the particle etc. Numerous mechanisms of erosive wear are exemplified in Figs.1.11 (a)-(e) for easy understanding of the readers. A low angle of impingement on wall surface of bend reveals the wear pattern analogous to abrasion as the material particles are found across the worn surface after impingement. A high angle of impingement causes wear mechanisms results in typical erosion. The wear process is strongly affected by the speed of the erosive particles. If the speed intensity is lesser, then stresses during impingement are inadequate for plastically deformation of the bend surface and the wear mechanism may be trailed by surface fatigue. When the intensity of the speed rises, it might be probable for the eroded material to deform plastically at higher rate. Wear may result from recurrent plastic deformation in this regime. As a result of increased plastic deformation, thin layers of worn-out material developed over the worn surface if the eroded particles were blunted or spherical. Cutting or brittle crumbling is more likely to occur if the impinged parts are sharp. On the other hand, brittle materials experience wear due to subsurface cracking. As

an example, melting of the affected surface may even happen at extremely high particle speeds shown in Fig.1.11 (e).

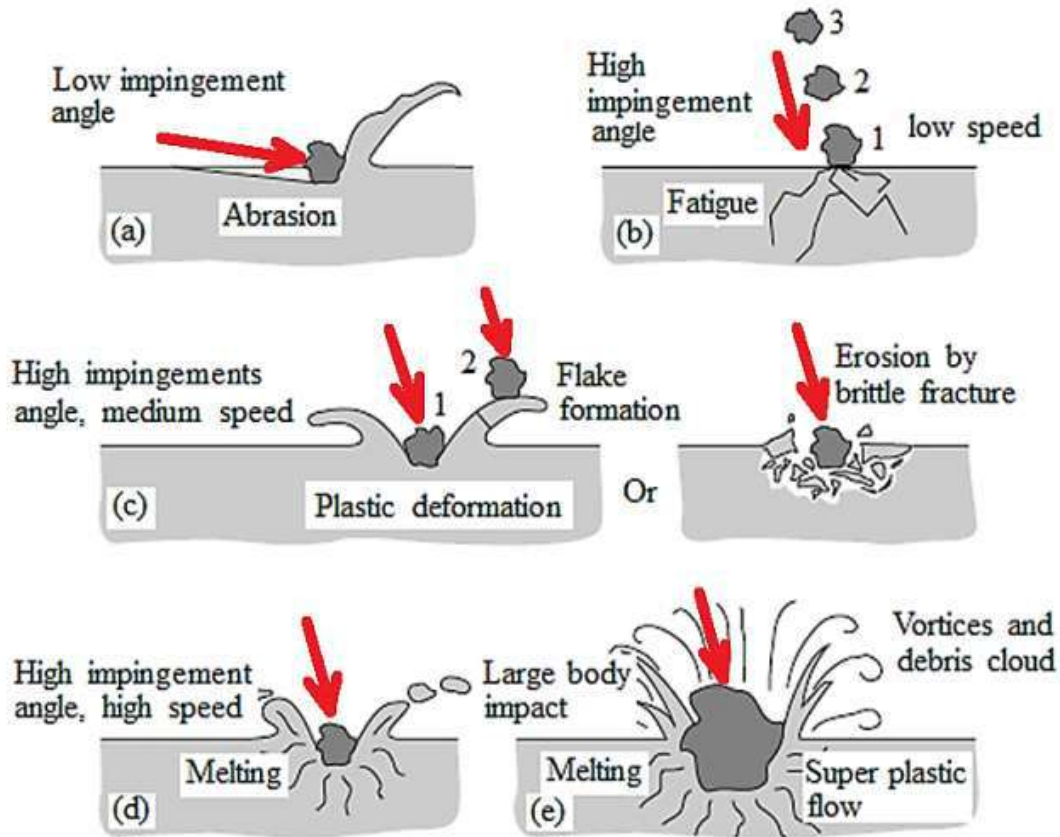


Fig. 1.11 Probable erosion mechanisms [2]; (a) Abrasion occurs at lower impact angles, (b) Fatigue during low speed and high impingement angle impact, (c) Brittle fracture or multiple plastic deformation during medium speed and large impingement angle impact, (d) Melting at high impact speed, (e) Erosion due to secondary effects

1.8.1 Parameters of pipe bend erosion

Parameters which used in pipe bend erosion are discussed below:

- i. Flow Velocity: Higher fluid velocities increase the energy of impinging particles, leading to higher erosion rates.
- ii. Particle Characteristics: Particle Size: Larger particles can cause more severe erosion.
- iii. Particle Concentration: Higher concentrations of solid particles in the fluid (slurry) lead to increased erosion.
- iv. Particle Density and Hardness: The density and hardness of the particles significantly affect the wear rate.

- v. Bend Radius (or R/D ratio): The R/D ratio influences the path of particles and the flow separation within the bend, affecting erosion.
- vi. Bend Angle: Erosion rates are often highest at specific bend angles, such as 30-50 degrees, and decrease at lower or higher angles.
- vii. Pipe Wall Thickness: Erosion defects caused by wear can impact the overall strength and buckling pressure of the pipe.
- viii. Wall Roughness: Increasing pipe wall roughness can decrease the penetration ratio (amount of material lost per mass of particles).
- ix. Turbulence: The turbulent nature of the flow, often modeled with a k-epsilon turbulence model, plays a role in particle transport and interaction with the pipe wall.
- x. Bend Erosion rate: While there isn't a single, universal formula for the rate of erosion in pipe bends, empirical models such as Finnie's model and others typically estimate it using the formula $Erosion\ Rate\ (E) = K * (Impact\ Velocity)^n * f(angle)$. In this case, $f(angle)$ is a function of the impact angle, whereas K and n are erosion factors that are dependent on the material qualities and procedure. Fluid velocity, particle mass flow rate, particle size, slurry concentration, and pipe bend geometry (such as the R/D ratio) are other crucial variables.

1.9 Factors affecting the erosion of pipe bend

In order to understand how to control erosive wear, it is essential to distinguish the factors/parameters affecting the erosion parameters in the pipe bends. Some of the factors such as angle of impact, impact speed, particle hardness, size of particle, solids loading ratio, pipe bend geometry, properties of bend materials etc. play vital role over the erosive wear. Role of these parameters on erosive wear of pipe bend are briefly described in the sub-sections to appear.

1.9.1 Impact angle and surface material

Difference of erosion rate having same impact angle for two diverse surface materials is shown in Fig. 1.12. Significant difference in erosion rate with impact angle of particle could be observed. Ductile material experiences extreme erosion at about 20-30° particle impact angle and bids decent erosion resistance to the usual impact. However, brittle material experiences extreme erosion under usual impact but bids decent erosion resistance to lower

angle of impact. Hence, brittle and ductile materials respond to erosion in a very diverse manner. This information can be useful in manipulating the impact angle and selecting the bend material.

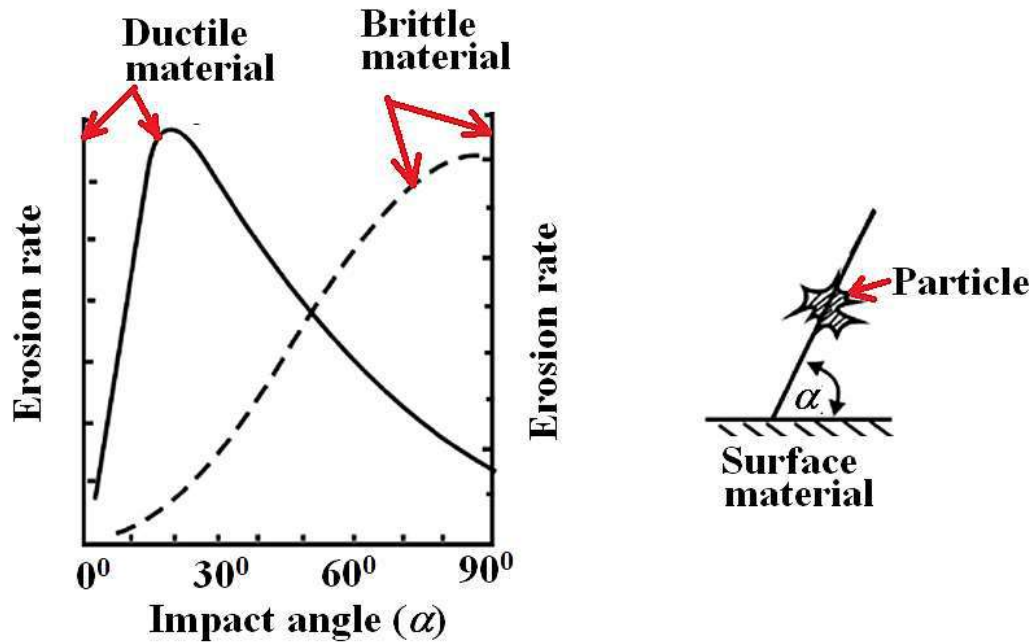


Fig. 1.12 Change in erosion rate with different impact angle [1]

1.9.2 Particle impact velocity and surface material

The particle's speed of impact put a very sturdy effect on wear rate. Negligible or very small amount of wear may be observed for threshold velocity value. In response of medium to higher impact velocities, the correlation among impact velocity and wear rate can be defined power law as follows:

$$\text{Erosion rate} = \text{constant} \times (\text{particle impact velocity})^n \quad (2.1)$$

There is confusion over the value of exponent (n) appearing in eqn. (2.1). In literature, it is reported that n varies in the range of 2–6. In Fig.1.13, it can be realized that all the curves are having almost identical slope irrespective of the surface materials. This slope comes out around 2.5 as reported in reference [1]. This slope is termed as exponent (n) appearing in eqn. (2.1).

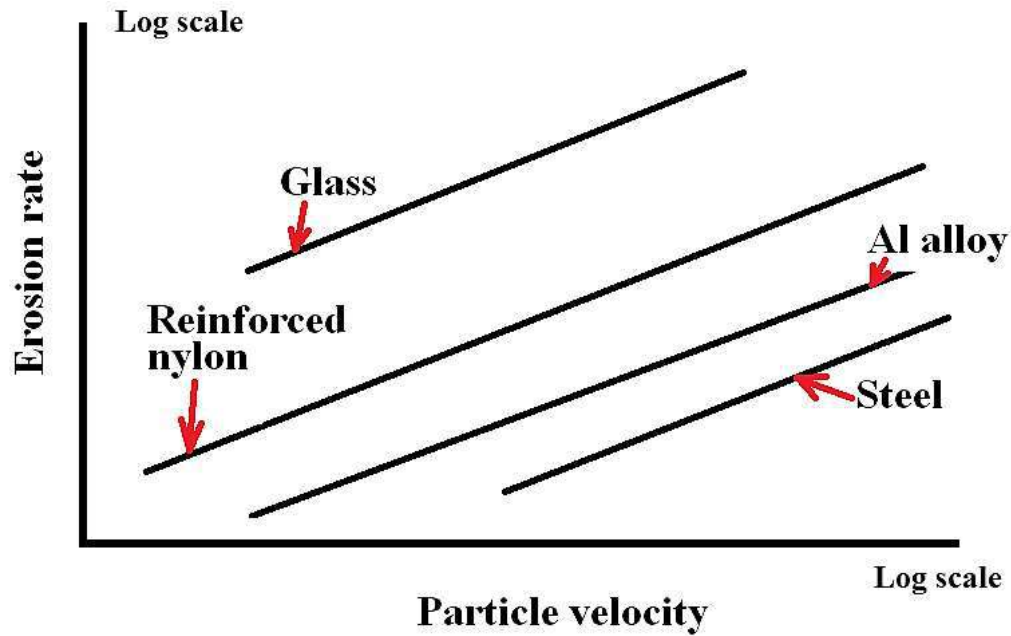


Fig. 1.13 Difference in erosion rate at different particle velocity [1]

1.9.3 Particle hardness

The hardness value of the particle conveyed is the indicator of the probable erosiveness of the material of bend. It has been reported in the literature that erosion rate increases with increase in the particle hardness (H_p , kg/mm^2) as per the following relation:

$$\text{Erosion rate} = \text{constant} \times H_p^{2.4} \quad (2.2)$$

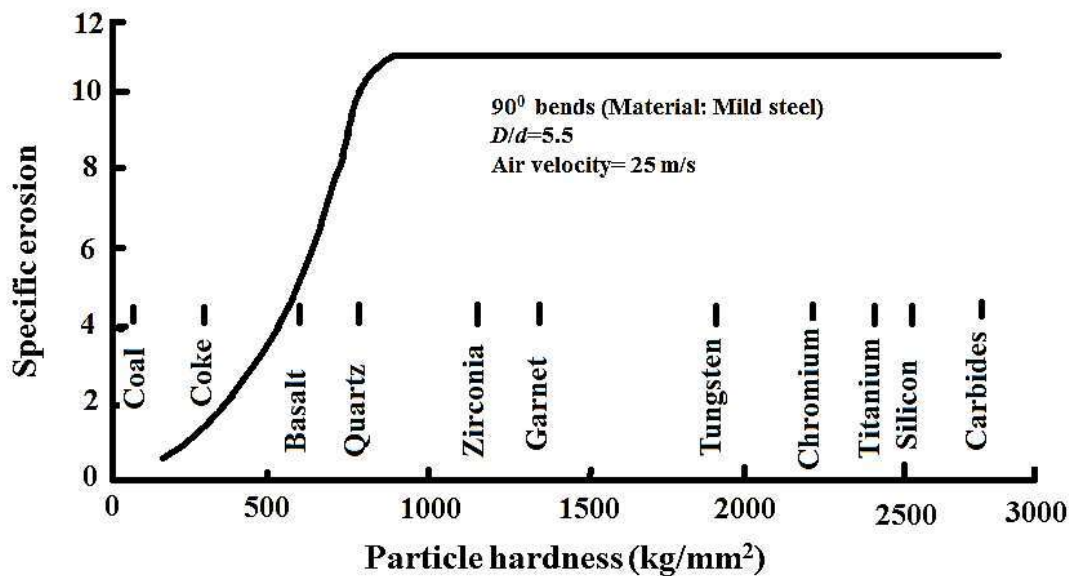


Fig. 1.14 Effect of particle hardness on the specific erosion of bends [1]

It is generally considered that there is a threshold value of particle hardness beyond which erosion rate remains essentially constant. This may happen at particle hardness of around 800 kg/mm^2 . Probable impact of particle hardness on the mild steel erosion is demonstrated in Fig. 1.14.

The hardness values of some commonly used materials, which include both conveyed materials and bend surface materials, have been laid out for easy understanding by readers. It can be perceived that coal is soft material and was improbable being a factor for erosive problem. But in actuality, both granular and pulverized and coals are erosive materials due to presence of quartz and alumina. With hefty tonnage flows, even insignificant proportions of such vastly abrasive crystals cause significant wear in the bends.

1.9.4 Particle size

The edgeless and globular particles don't trigger significant erosion of strident angular shape particles under analogous circumstances for velocity impact, hardness of particle with the surface materials. In experimental study of erosive wear in bends within pneumatic conveying pipeline system, there is usually a prerequisite of the transported material to be re-circulated. Consequence of re-circulating the impinging particle, it lowers the strident angular shape bends associated the edges of the even new material are progressively worn away, and this converts into more smoothed and later pointedly less erosive in nature. With increase in particle size, a threshold value of wear rate reaches at the particle size of $60\mu\text{m}$. With smaller than this size of particle, the wear rate diminishes. But for particle sizes bigger than $60\mu\text{m}$, it remains almost persistent. However, this threshold value increases with increase in particle velocity. Fig. 1.15 illustrates the threshold value increase with increase in the impact velocity. In this Fig. 1.15, the wear rate is articulated in explicit terms i.e. the mass (or volume) of eroded surface material per unit mass of impinged particles. For a certain mass of particles, the number of particles will diminish as the particle size surges. Thus, the explicit erosion remains unchanged, except for a surge in particle size. Though the erosive wear per particle rises roughly by the cube of the particle size. Very few works have been undertaken with particle sizes greatly larger, i.e. above $1000\mu\text{m}$, and consequently, till now, it is not confirmed that up to what particle size the threshold value remains persistent.

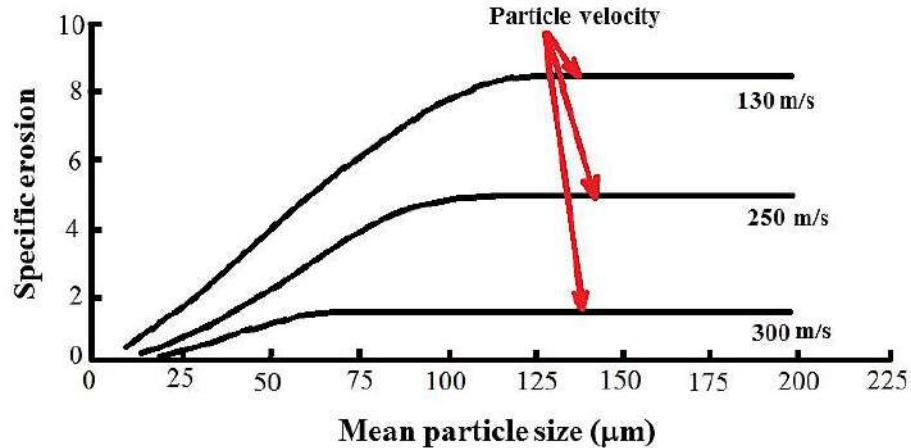


Fig. 1.15 Effect of size at different velocities of particle on erosion [1]

1.9.5 Solids loading ratio

Inconsistent particle concentration has received slight attention in the basic research work with respect to the topic. There is little information available indicating decrease in erosion for a large solids loading ratio. Fig. 1.16 demonstrates information pertaining to failure of bends with solids loading ratio for the input data indicated along the graph.

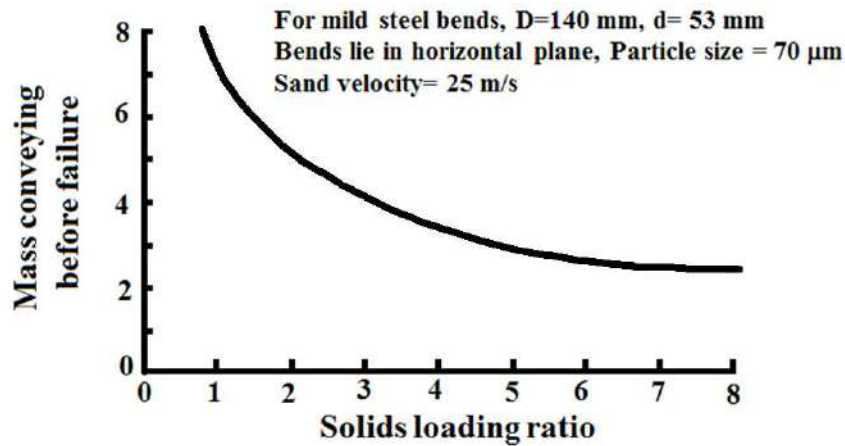


Fig. 1.16 Effect of solids loading ratio on the bends conveying capacity [1]

1.9.6 Bend geometry

From prolonged radius bends to constricted elbows and mitered bends, bends are available in a wide variety of geometries in respect to the bend curvature. Bends are prone to wear, hence several studies and innovations have been made to address the issue. The erosion findings for 90° bends of mild steel material are displayed in Fig. 1.17 over a broad range of D/d values. Sand particles carried at a solids loading ratio of two while maintaining a

conveying air velocity of 25 m/s had corroded the bends. The worst-case scenario is roughly represented by a bend with $D/d = 6$. The bent surface will be struck by the greatest amount of particles at an angle of about 20° .

. In the case of a material that is ductile in nature, the outcome is in the form of extreme erosion, which has resulted in the swift failure of the bend. Particle impinged on the bend surface having a D/d ratio around 20 results in a much shallower angle. In case of moderately small impact angle, the erosion may not be too harmful, thus, it may be anticipated that the bend could not wear too swiftly.

A slight impact angle is an crucial pre-requisite for diminishing erosion among the brittle surface materials. While in case of materials ductile in nature, as the oddly abrupt increase in erosion is observed for very slight angle of impact, elongated radius bends would be obligatory. It is expected to estimate the association among the bend geometry (D/d) and the impact angle. The outcomes of such an investigation are presented in Fig. 1.18.

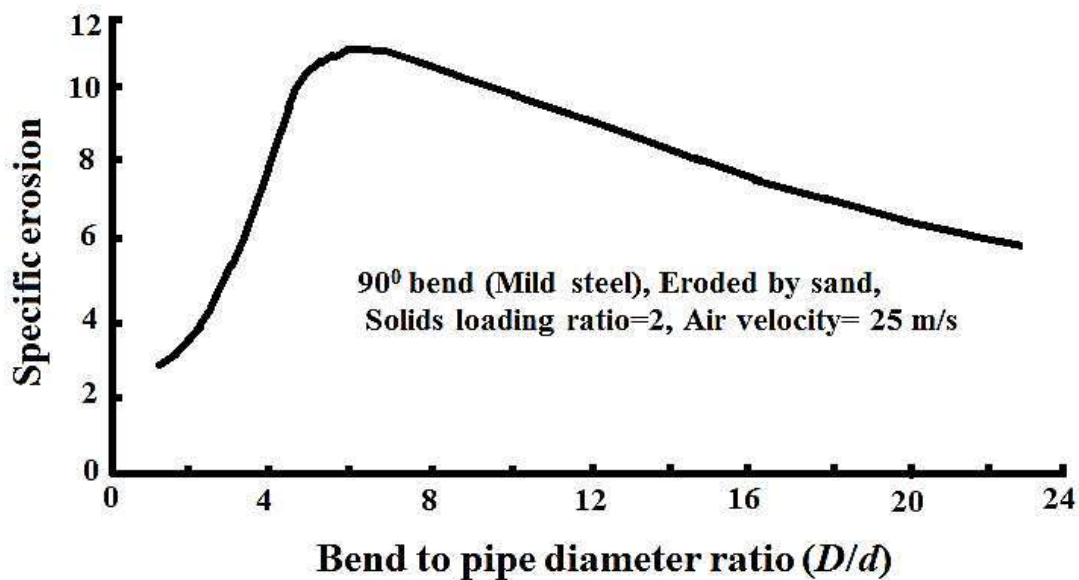


Fig. 1.17 Impact of geometry on the bend's specific erosion wear [1]

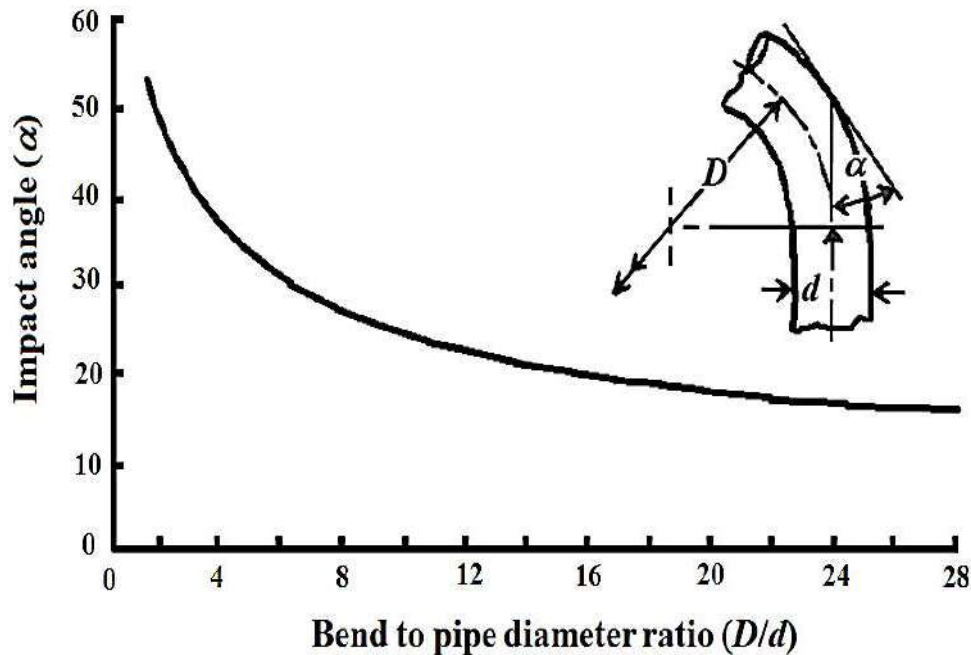


Fig. 1.18 Effect of bend geometry on impact angle of particles [1]

For ductile materials, stretched radius bends are not liable to be a workable suggestion. A usual method of offering a segmented bend for stretched radius bend. Such observations will be due to a lighter bend in weight and easier to be fitted into the pipeline. Since the maximum observed wear will be at the impact point primarily, henceforth one or more segments needs replacement in case of failure. The overall life of the bend can be extended by reversing and interchanging bend segment.

1.9.7 Surface finish

It's commonly thought that a well-polished surface will slow down erosion, but this only works for a short time. It mainly reduces the wear rate. Surface textures have a minor impact on the steady state erosion rate once the surface material begins to wear. Moreover, erosive wear is most likely to occur in brittle materials with permeable surfaces.

1.10 Benefits of pneumatic conveying system (PCS)

PCS are used in various engineering among the main advantages that pneumatic conveying offers are increased safety, flexibility, reduced material waste, reduced maintenance, space-saving design, and increased efficiency. These systems use air pressure to transfer materials

through enclosed pipelines, reducing contamination, spillage, and operator exposure to hazardous substances. Benefits of pneumatic conveying:

- Efficiency- When moving heavy loads, pneumatic conveying equipment uses a lot less energy.
- Flexibility- They can handle a range of materials, including abrasive, fragile, and hygroscopic compounds, and they can be routed both horizontally and vertically.
- Reduced material waste-Because enclosed systems prevent material leakage and contamination, cleaner facilities and less waste are produced.
- Low maintenance-less wear and tear results with fewer moving parts, which lowers maintenance expenses and downtime. Fewer moving parts translate to less wear and tear, reducing maintenance costs and downtime.
- Space-saving-Pneumatic systems can be employed with a range of plant configurations due to their compact size and ease of integration into existing designs.
- Reducing manual handling lowers worker exposure to dangerous materials and injuries.
- Dust control-by keeping dust confined, enclosed pipelines enhance worker hygiene and safety.
- Cost-effectiveness -Automation lowers labour expenses, and minimal maintenance requirements contribute to overall savings.
- Material Compatibility- Pneumatic systems can control certain material qualities, guaranteeing the integrity of the final product.
- Customization- Pneumatic systems can be modified to accommodate particular material handling requirements and industrial layouts.

1.11 Application of pneumatic conveying system

PCS had applications in Food Processing, Pharmaceutical, Chemical and Petrochemical, mining and Cement industries, Agriculture, Plastic Industry and other industries explained below: -

- Food Processing: Pneumatic conveying systems are used to transport materials like flour, sugar, spices, and other bulk materials, ensuring hygiene and preventing

contamination, bulk goods such as flour, sugar, spices, and other ingredients are transported using pneumatic conveying systems.

- **Pharmaceuticals:** utilized to transport granules, powders, and active medicinal ingredients, assisting with cleanroom procedures and regulatory compliance.
- **Chemicals and Petrochemicals:** These systems are used to properly handle hazardous materials while transferring chemicals, catalysts, and polymers.
- **Mining and Cement:** To minimize material loss and guarantee effective bulk handling, pneumatic conveying is used to move minerals, coal, and cement.
- **Agriculture:** Transporting grains, seeds, and fertilizers improves productivity and guards against contamination in agriculture.
- **Plastics Industry:** They streamline industrial processes by transporting plastic pellets, resins, and powders.
- **Other Industries:** In addition to recycling applications, pneumatic conveying finds employment in the steel, power, and rubber sectors.

1.12 Challenges of PCS

Problems/ challenges in pneumatic Conveying systems are categorized in material-related challenges and system-related challenges

1.12.1 Challenges associated with materials

Different types of materials cause problems in the pneumatic Conveying System discussed below:

- i. **Fragile Materials:** The quality of the final product may be impacted by the breaking or degradation of fragile materials due to high speeds and pipeline bends.
- ii. **Abrasive Materials:** These substances have the ability to erode pipelines, resulting in leaks and possible pollution.
- iii. **Cohesive and sticky materials** have the tendency to group together, obstructing flow and causing obstructions.
- iv. **Wet or Hygroscopic Materials:** Moisture can make materials difficult to move or cause them to clump together, which could result in obstructions.
- v. **Particle Density and Size:** It can be challenging to transport materials with high densities and large particle sizes, particularly in diluted-phase systems.

- vi. Material Segregation: During conveying, various particle densities or sizes may segregate, compromising the homogeneity of the final product.

1.12.2 Challenges associated with the system

PCS faces the following problems during the transportation of materials.

- i. Blockages: Consistent material flow, insufficient air velocity, and material properties can cause blockages in the pipeline.
- ii. Pressure Drop: Bends, lifts, and material friction in the pipeline can cause pressure drops, affecting conveying efficiency.
- iii. Attrition: Friction between particles and pipeline walls can cause material degradation (attrition).
- iv. Bend Erosion: Abrasive materials can wear down the pipeline, especially at bends, due to the bombardment of particles.
- v. Dust Control: Open-circuit systems may release dust into the atmosphere, requiring dust collection and potential authorization.
- vi. Energy Consumption: Pneumatic conveying can be less energy-efficient than mechanical conveying, especially at higher throughputs.
- vii. System Complexity: Optimizing system design for different materials and operating conditions can be complex.
- viii. Maintenance: Regular maintenance is crucial to prevent blockages, wear, and other issues.
- ix. Dust Control: Utilize cyclones and filters to capture dust particles.
- x. Product Damage: Ensure the system is designed to handle the specific material's properties and consider using a mechanical conveying system for particularly fragile materials.

The pneumatic conveying system had a bend erosion issue, which is detrimental for the concerned industries. Industries and researchers had made bends with replaceable back, interchangeable backup bend, concrete strengthened bend, plate welded strengthened bend, corrugated arrangement to face this problem of bend erosion. Erosion wear is a typical type of wear in which abrasion, fatigue, plastic deformation, melting and super plastic flow happen spontaneously hence it is very detrimental wear. Ductile material experiences extreme erosion at about 20-30° particle impact angle. Bend material and hardness had very limited effect on erosion reduction. As Mean effective particle size of transport particles

increases then bend erosion rate increases. As Solid loading ratio, bend to pipe diameter ratio increases bend erosion rate decreases. Pneumatic conveying system had application in food processing, pharmaceutical, petrochemical, agriculture, mining, cement and plastic industries due to cost effectiveness.

CHAPTER 2

LITERATURE REVIEW

The work of various researchers and scientists in this pneumatic conveying field was thoroughly discussed, and their contribution is summarized in this chapter. Objectives, guidelines, and path for research for the present work were also taken from this rigorous literature review of these researchers and act as a pathfinder for the present work. This chapter is a light of torch for carrying out research in large prospects.

2.1 Literature review

The exhaustive literature review has been carried out for the study of erosive wear in metallic pipe and classified as below: -

i.) Parameters affecting the erosive wear of pipe bend ii.) Swirling Flow effect on Pipe bend erosion rate iii Numerical Analysis on pipe bend erosion rate iv.) Erosion Corrosion paper v.) River Bank bend erosion vi.) General Bend Erosion Papers

2.1.1 Parameters affecting the erosive wear of pipe bend

Numerous studies have worked to understand how different characteristics (particle impact angle, impact velocity, particle hardness, particle size, solid loading ratio, bend geometry, bend material, bend surface quality, etc.) affect pipe bend wear [5-8].

Based on their analysis of the data, Burnet et al. [5] concluded that the particles' concentration against the outside bend wall and the shape of the pipe bore caused them to bounce back toward the center line of the pipe bore following the initial hit. In the area where the secondary impact predominated—where puncture took place—this behavior intensified particle strikes.

Fokeer et al. [6] have given a good summary of the literature on pneumatic conveying using horizontal pipeline. In this paper, the results of recent investigations into horizontal pneumatic conveying of materials in the diluted phase are reviewed and analyzed. Pneumatic conveying in the diluted phase is presented. Many in-process applications require detailed knowledge of the cross-sectional particle concentration distribution, and a review of the literature in that field is given. A summary is given of the various technologies

that can be used to achieve the goals of such a study, including computational fluid dynamics (CFD) modeling and tomography.

Hilton and Cleary [7] define pneumatic conveying as the process of employing an imposed gas flow to move particles via pipes or ducts. Granular flow in these systems is highly dependent on the imposed gas flowrate and can be categorized by a particular set of modes. These flow patterns include slug flow, where a slowly moving mass of material blocks the pipe's bore, moving dunes, and diluted flow, where the grains are fully suspended in the gas. The transitions between these modes must be understood in order to design and deploy pneumatic conveying systems. Particle shape is a crucial factor to take into account in systems with gas-grain interactions.

Behra et al., claims that in fluidized dense phase pneumatic conveying, pressure loss is a result of frictional interactions between the gas, particle, and pipe wall. Several scholars have proposed numerous correlations to predict the pressure drop in fluidized dense phase conveying. The steady state flow equations for many phases are presented in this paper and are solved under the assumption of particular characteristics for different conveying materials. A single gas phase and a specific number of solid phases selected based on the conveying material's particle size distribution are taken into consideration while developing the flow equations. The values of the flow parameters have been established at the pipeline's exit using experimental data as initial conditions. By imposing specific limiting conditions of conveying, experimental results have also been used to determine the maximum possible conveying distance or maximum possible conveying pipeline diameter. The pressure drop for various pipeline diameters and lengths has been predicted using scaling equations for the solids mass flow rate and the air mass flow rate. Table 2.1 displays the parameters associated with the erosion rate illustrated literature review.

Table 2.1 Parameter affecting erosion of pipe bend

S. No	Authors/ tool used	Study topic	Results
1	Fokeer et. al, [6] 2004 used CFD and	A. Reynolds Characterization of the cross sectional particle concentration distribution in	The optimal operating parameters for enhancing system energy efficiency and reducing pipe wear were discovered through testing of

	Tomatography	horizontal dilute flow conveying—a review	pneumatic conveying of materials in the diluted phase.
2	Hilton et. al, [7] 2011 Used Experimental data	The influence of particle shape on flow modes in pneumatic conveying	Particle form has so far been neglected in models of pneumatic transportation, despite being an important consideration in systems with gas–grain interactions. We demonstrate that particle shape has a significant role in the transition between various flow modes through simulations Series utilizing the discrete element technique for gas flow.
3	Behra et. al, [8] 2013 used Experiment on pneumatic conveying system	Modeling and analysis for fluidized dense phase conveying including particle size distribution	In fluidized dense phase pneumatic conveying, frictional interactions between the gas, particle, and pipe wall result in a drop in pressure. Several scholars have proposed numerous correlations to predict the pressure drop in fluidized dense phase conveying.
4	Bankermani et. al,[27] 2018 Used Erosion model	An investigation of erosion prediction for 15 to 90 elbows by numerical simulation of gas-solid flow	Data prediction for a typical elbow with a 90° angle and a diameter of 76.2 mm. The final step involves simulating a range of elbow angles for two distinct flow orientations: vertical input flows with flow at outlet that will lie in the horizontal plane to form certain angles of flow (V-H flow) and horizontal inlet and outlet flow directions (H-H flow).
5	Zhu et. al.,[53]	Numerical Investigation of Temperature Distribution in	Determination of the temperature distribution in a bent pipe that has been

	2014used CFD with Fluent	an Eroded Bend Pipe and Prediction of Erosion Reduced Thickness	damaged and develop a novel technique to forecast the thickness that erosion has reduced. The thickness reduced by erosion reduced, which is required to track the bent pipe's temperature of outer surface, can be computed by fluid flow equations
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2.1.2 Swirling flow effect on wear of pipe bends erosion rate

Researchers have tried to create swirl flow by using the different types of geometry and got the patent of same some patents are shown and explain below and Illustrative swirling flow effect on pipe bend is shown in Table 2.2.

US patent by Gordon et al., [10] have casted strip inside the pipe tpo induce swirl flow as shown in Fig. 2.1

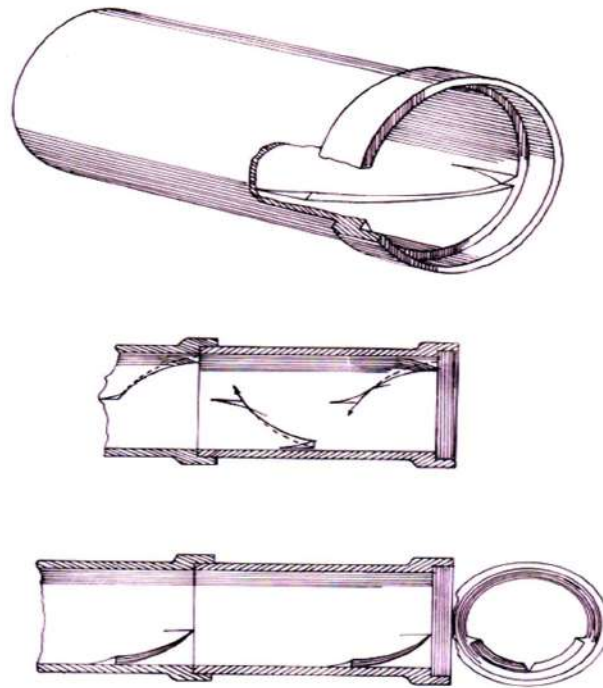


Fig. 2.1 Swirl mechanism [12]

Swirling by Robinson[11] shows strip inside the pipe to make swirl flow as shown in Fig. 2.2.

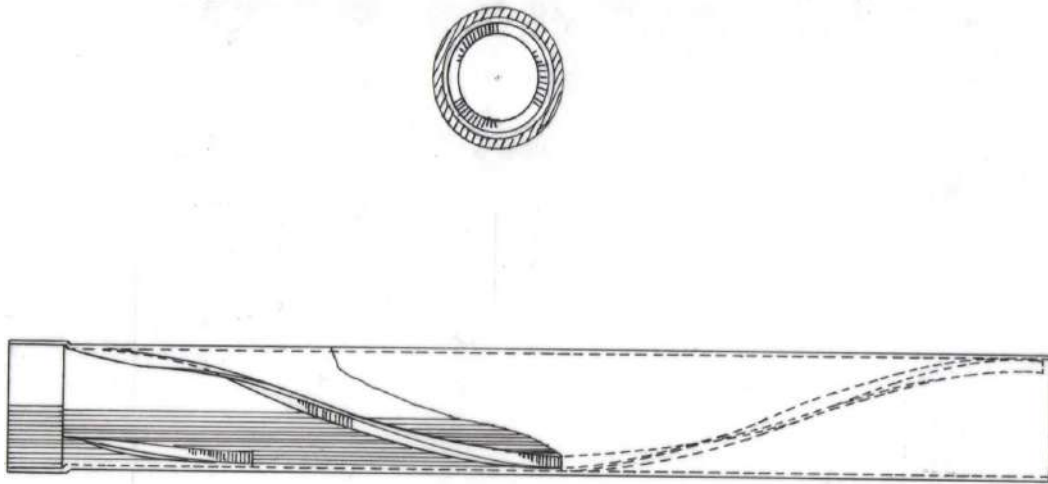


Fig. 2.2 Swirling by Robinson [13]

Patent by Yuille [12] also insert blade in systematic manner as shown in fig 2.3 pipe to reduce erosive wear.

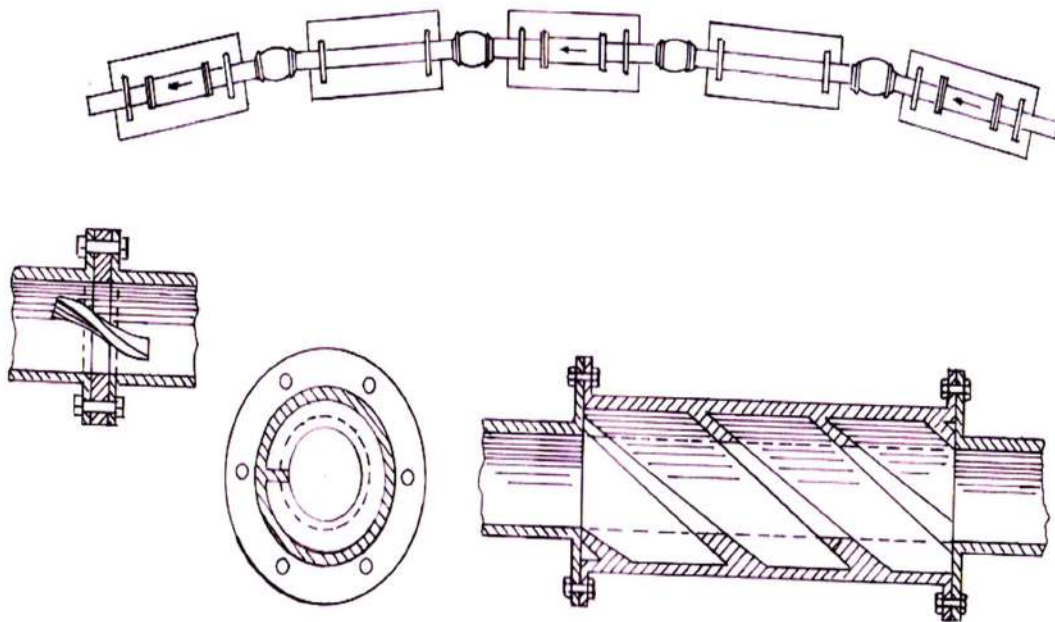


Fig. 2.3 Patent by Yuille [14]

Patent for transporting slurries by Wolfe [13] has inserted the twisted strip in spiral shape as shown in Fig. 2.4

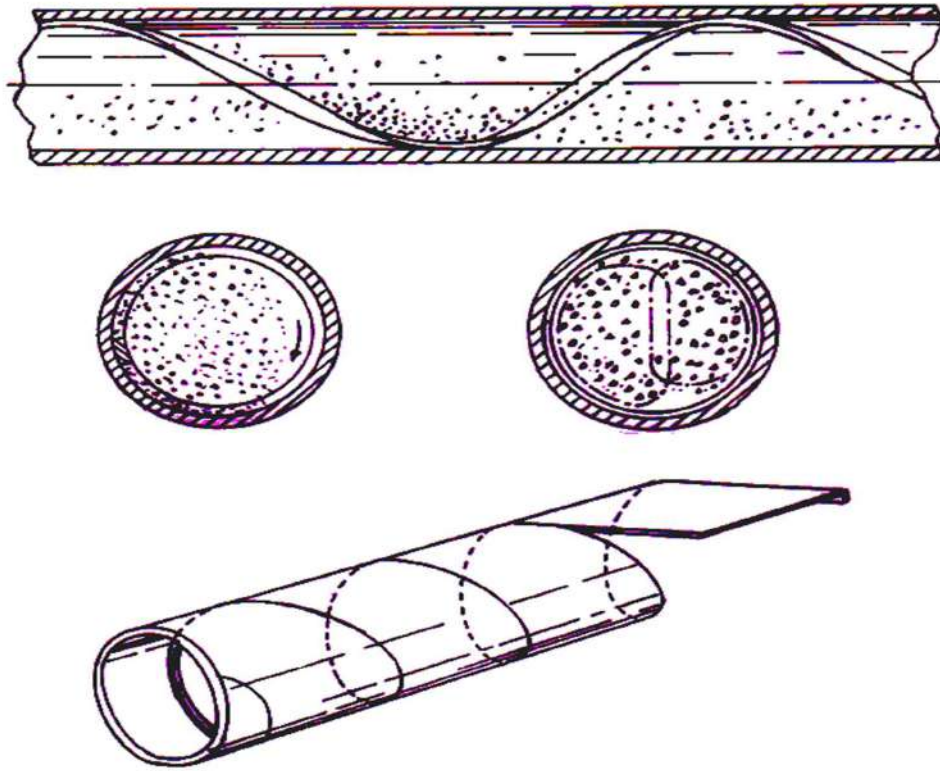


Fig. 2.4 Patent for transporting slurries by Wolfe [15]

US patent by Garbo [14] had inserted the air as Shown in Fig. 2.5 in bend to reduce wear with Swirl flow.

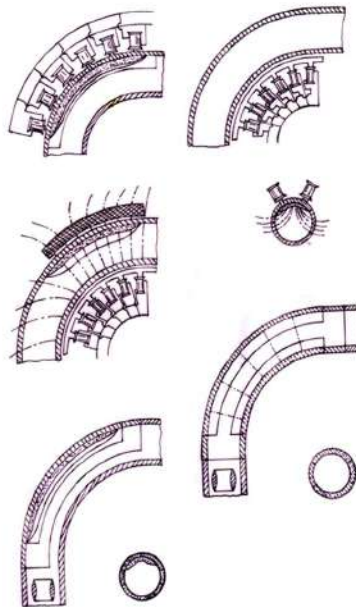


Fig. 2.5 Patent by Garbo [16]

Table 2.2 Swirl flow in pipe bend

S. No.	Authors/ tools used	Study topic	Results
1	Gordon et. al, [9] 1899 used Casted strip in Pipe geometry added	Conduit or pipe, U.S. Patent No.630605	Induce swirl flow
2	Robinson et. al, [10] 1923 used Long curved strip added	Delivery pipe for hydraulic dredging machines	Induce swirl flow
3	Yullie et. al, [11] 1928 Used Attachment made and blade inserted	Dredger pipe line, US Patent No. 1662178	Induce swirl flow
4	Garbo et. al, [12] 1951 used Air Induced at bend to reduce wear	Method and apparatus for transporting slurries, US Patent No: 3313577	Air induction in bend reduce erosive wear
5	Wolfe [13] et. al, 1967 Used inserted Tape	Prevention of erosion my moving solids, US Patent No. 2578003	Induce swirl in particle motion
6	Field et. al, [15] 1996 Developed storm flow swirl vortex form	Swirl technology: enhancement of design, evaluation, and application	reduction of erosive wear by this vortex flow leads to cost reduction
7	Li et. al, [16] 1999 used	An experimental study on a horizontal swirling flow	In comparison to the naked tube, it is found that the

	Helical finned tube is put up in use in ash handling	pneumatic conveying with a curved pipe	helically finned tube not only enhances heat transfer but also offers remarkable protection against ash deposition and wear, which is greatly diminished.
8	Li et. al, [17] 2000 used Axial flow pneumatic conveying (AFPC)	Particle velocity and concentration characteristics in a horizontal dilute swirling flow pneumatic conveying	These systems need significant pressure drops and are initially costly. Furthermore, at low conveying velocities, Dense-phase pneumatic conveying may produce unstable flows
9	Li et. al, [18] 2000 used Horizontal dilute swirling flow pneumatic conveying	Characteristics of a horizontal swirling flow pneumatic conveying with a curved pipe	SFPC proved to be effective in the low velocity conveyance range,. In contrast, SFPC two-phase flows of gas-particle are a complicated and unstable system of nonlinear dynamics. An in-depth understanding of particle behavior is necessary for the design, optimization, and operation of an SFPC system.
10	Wood et. al, [18] 2001 swirl can get particles into suspension at lower pumping power and lower pressure drop	Upstream swirl-induction for reduction of erosion damage from slurries in pipeline bends	Particle solids in suspension required low minimum velocities to keep, flows were easily stopped and started, and lower particulate velocities may reduce wear.

	than a conventional round duct		
11	Fokeer et. al, [19]2009 used CFD	An experimental investigation of pneumatic swirl flow induced by a three lobed helical pipe	The helical pipe's capacity to produce a swirl or tangential component in the flow field can increase axial velocities and may be advantageous for the Dilute pneumatic conveying phase and transfer of heat. Swirl-inducing pipes have the advantage of lower conveying velocities and pressure drops than conventional axial pneumatic conveying, which leads to lower power usage.
12	Alkassar et. Al [20] 2019 used Pneumatic conveying system experiments	Transient characteristics of fine powder flows within fluidized dense phase pneumatic conveying systems	The moving bed flow has pulsatile phenomena and transient properties that are defined by random frequencies and varying amplitudes, according to the wavelet analysis (Daubechies db4 wavelet) of air pulse signals. Throughout the pipeline's length, different pulse structures have been produced by the constant aeration and de-aeration of dunes during conveyance. The pulse structures of several types of bulk materials have

			also been demonstrated to differ significantly.
13	Zahedia et. al, [40] 2019 used gas-liquid-solid flows are often observed in oil and gas transmission pipelines	Experimental investigation of sand particle erosion in a 90° elbow in annular two-phase flows	The behavior of the particle phase and liquid dispersion were examined through studies on paint deterioration and flow visualization.
14	Yadav et. al [44] 2014 Used patented Swirling device Experiment	Study for Reduction of Erosive wear in Pneumatic Conveying Pipe Bend By Developing a Swirling Device	Erosive wear is reduced upto 70 % using swirling device.
15	Farokhipour et. al, [46] 2020	study of Particle Mass Loading Effect on sand erosion in series of fittings	In a series of 90-degree fittings, erosion is evaluated using gas-solid flow modeling. different coupling models are used to calculate erosion rates, in order to avoid blocked tees and steep bends, inter-particle collisions are essential. The cushioning effects for these features are strengthened with an increase in sand rate. The bend that is most resistant to erosion at high and moderate mass loadings is the plugged tee.

16	Cao et. al,[47] 2020 Used 316 L stainless steel elbow used in experiments	Effect of superficial air and water velocities on the erosion of horizontal elbow in slug flow	The research findings show that the erosion rate by an increase in superficial air velocity is more affected than by an increase in superficial water velocity. The external wall at the 67.5° angle sustains the highest erosion damage.
17	Kumar et. al, [50] 2020 used Experiment by changing swirl vane angle and CFD	Effect of swirl vanes angle on erosion behavior of AISI 316 pipe bend	Three different 7.5 swirler sites are used in the CFD software. The swirler is positioned, in order, 280 mm, 320 mm, and 360 mm for upstream pipe entry. The CFD-calculated wear for three cases has been plotted.

2.1.3 Numerical investigation of erosive wear in pipe bend erosion rate

The various researchers have made different type of mathematical model for erosive wear in pipe bend to find the effect by various methods given in table 2.3.:

Table 2.3 Mathematical modeling of pipe bend erosion

S. No.	Reference	Study topic	Results
1.	Lain et. al, [21] 2019 used Euler approach	Numerical prediction of particle erosion of pipe bends	Bend erosion is reduced and particle mass loading is increased by varying the particle impact velocity and angle.
2.	Zhang et. al, [22] 2019 used New model which is verified by	Approximate theoretical solution of the movement and	There are some special circumstances in which this complex process can be solved. However, it is still

	comparing the prediction	erosion of solid particles in a 90° bend	unable to confirm the particle movement anticipated by the current model due to the lack of pertinent experimental evidence.
3	Agarwal et. al,[23] 2019 used CFD model	Prediction of sand erosion in CFD with dynamically deforming pipe geometry and implementing proper treatment of turbulence dispersion in particle tracking	When crude oil is delivered through pipes in unconsolidated petroleum reservoirs, solid particles are present. Because during crude oil production, these particles are often transported as dispersed phases, they are very detrimental to the integrity of the pipe surface. This could start crevice corrosion because of the erosion of the pipe. Given this description, the aim of this paper is to investigate the dynamics of crude oil as it travels through pipelines and locate erosion hotspots the reynolds averaging navier-stokes (RANS) for different pipe elbow curvatures. and Particle Tracing Modeling (PTM) methods were used.
4	Zhang et. al, [25] 2019 used CFD	A comprehensive CFD-based erosion prediction for sharp	A comprehensive prediction of erosion based on CFD procedure that was previously

		bend geometry with examination of grid effect	established is used to forecast erosion in a 90° sudden turn. This paper further validates the proposed prediction by the Computational Fluid Dynamics (CFD) based erosion model approach for a different form by examining the major influence of the grids on the final erosion profile representation.
5	Arun et. al, [26] 2019 used Sharp and mitred bend are used and same investigated with turbulence model	Numerical Predictions of fluid dynamics and wall erosion characteristics in a circular 90 deg. pipe bend with single and multi joint	With certain mesh configuration choices, a typical to simulate the flow by k-e model through the 90-S and 90-M pipe bends. It is clear that the first and second acute turning pipe bends have the highest and lowest flow velocity values, respectively.
6	Duarte et. al, [29] 2019 used CFD	A numerical assessment of two geometries for reducing elbow erosion	With certain mesh configuration choices, a typical k-e model used to simulate flow through 90-S and 90-M pipe bends. It is clear that the first and second acute turning pipe bends have the highest and lowest flow velocity values, respectively.

7	Ejeh et. al, [30] 2020 Used CFD and RANS	Computational fluid dynamic analysis for investigating the influence of pipe curvature on erosion rate prediction during crude oil production, Experimental and Computational Multiphase Flow	When crude oil is delivered through pipes in unconsolidated petroleum reservoirs, solid particles are present. Because during crude oil production these particles are often transported as dispersed phases, they are detrimental to the integrity of the pipe surface. This could start with crevice corrosion because of pipe erosion. Given the above description, the aim of this paper is to investigate the dynamics of crude oil as it travels through pipelines and locate erosion hotspots for different pipe elbow curvatures.
8	Kannojia et. al, [31] 2018 used CFD, Ansys CFX	Numerical Analysis of Solid Particle Erosion in Pipe Elbow	There is an established correlation between erosion rate density and solid concentration and the. The erosion density is found to be four times higher when the solid contamination from 2 to 8% increase at a speed of 5 m/s.
9	Wee et. al, [32] 2019 used sand	CFD study of sand erosion in pipeline	on elbow erosion behaviour has been investigated with effect of the bending angle.

	erosion behavior in 76.2mm		The erosion hotspot found to have shifted from the downstream pipe when the bending angle increased from 30° to 90° on the elbow section. There was a 67% reduction in erosion at a bending angle of 300.
10	Liu et. al, [34] 2019 used numerical procedure is carried out to forecast the penetration rates of metal elbows caused by silica sand particles under air-water annular flow conditions	A numerical procedure for estimating the sand erosion of elbows in annular flow with the complete thickness distribution of the liquid film	The effective collision intensity of the particles is strongly dependent on the velocity and thickness distribution of the liquid film. By using the entire liquid layer thickness information, the proposed technique shows good accuracy in estimating elbow erosion under annular flow conditions.
11	Pei et. al, [35] 2018 used the erosion behavior in elbows, the flow field, particle trajectories, and used the erosion behavior in elbows, the flow field, particle trajectories, and relationship	Numerical investigation of the maximum erosion zone in elbows for liquid-particle flow	The results show that (1) the maximum erosion zone is directly proportional to the particle diameter; (2) the eddy influences the maximum erosion zone, but the location of the eddy is not significantly impacted by the Stokes number for particle motion in the elbow; and (3) increasing the radius of curvature will change the

	between the relationship between the dynamic cfd		flow field in the pipe and, thus, the location of the maximum erosion zone.
12	Singh et. al,[36] 2018 used CFD fluent	CFD modeling of erosion wear in pipe bend for the flow of bottom ash suspension	The Euler-Lagrange model was used to forecast the solid particle erosion wear at a 90° pipe bend for the flow of bottom ash–water suspension. A standard k–ε turbulence modeling scheme was used to simulate the flow through the pipeline. Water was regarded as a liquid, while bottom ash was regarded as a dispersed phase of a solid-liquid mixture. A simulation research for erosion wear in a pipe bend was used to investigate the effects of several parameters, including particle size, solid concentration, and velocity. For solid concentrations between 2.5 and 10.0% (by volume), the velocity of the bottom ash–water suspension varied between 0.5 and 2.5 m/s.
13	Zhang et. al,[43] 2012 used DEM	Francesc Xavier Trias, Shengqiang Numerical investigation of the	The locations of the puncture points and the wear pattern in the elbow were correlated

		location of maximum erosive wear damage in elbow: Effect of slurry velocity, bend orientation and angle of elbow	with the spatial distribution of particle–wall contact force. Specifically, the effects of elbow angle, bend orientation, and slurry velocity on the location of the puncture site
14	Frokipur et. al, [49] 2020 used computational modelling	3D computational modeling of sand erosion in gas-liquid-particle multiphase annular flows in bends	a higher gas velocity leads to a higher impact velocity of particles and increases erosion
15	Peng et. al, [51] 2020 used CFD	Experiment and numerical simulation of sand particle erosion under slug flow condition in a horizontal pipe bend	The pipe bend is most severely corroded at the axial angle of the elbow, which is between 67.5 and 90, and the circumferential angle, which is between 45 and 90. The erosion properties of the pipe wall are dominated by three particle impact mechanisms.
16	Zhang et al, [52] 2020 used numerical simulation of solid particle erosion	Random process of particle-wall collision and its application in numerical simulation of solid particle erosion	The numerical modeling of solid particle erosion of two orthogonal plates and 90 bends is then conducted using the combination of the rough wall and soft ball models. By comparing with the experimental data that is available in the literature, the model combination is thoroughly validated.

2.1.4 Erosion corrosion combined mechanism effect in pipe bend

Illustrative literature on erosion corrosion combine effect is shown in table 2.4.

Table 2.4 Literature review of erosion corrosion combine effect

S. No	Authors and Tools Used	Study topic	Results
1	Zeng et. al,[41] 2017 Inhibition effect of inhibitor on the erosion-corrosion (E-C) of a low alloy steel bend is investigated by weight loss, electrochemical measurements, and surface analysis.	Inhibition of the erosion-corrosion of a 90° low alloy steel bend, Alloy and compounds	The intrados have higher inhibitory efficiency (IEs) than the bend's extrados for total E-C, pure erosion, corrosion-enhanced erosion, and erosion-enhanced corrosion. The negative hydrodynamic conditions and strong sand particle impact at the extrados are the causes of the lower IEs there.
2	Zeng et. al,[42] 2018 Semi conductivities of passive films at a stainless steel bend in sand containing NaCl solution under erosion-corrosion (E-C) conditions were investigated by Mott-Schottky analysis.	Semi conductivities of passive films formed on stainless steel bend under erosion-corrosion conditions	The semi-conductivities of passive films are significantly influenced by the hydrodynamic characteristics close to the bend.
3	Elemuren et. al [48], 2020 Micro structural examination of the elbows that suffered erosion-corrosion	Microscopic And Spectroscopic Study Of Erosion-Corrosion Of Aisi 1018 Steel Elbows In	Particle concentration and their interaction were the next most important factors influencing the erosion-corrosion rate, after flow velocity. Approximately 87% of the elbow's overall erosion-

	damage indicated cutting, horseshoe-shaped depressions and pitting corrosion as the primary forms of damage to the elbow surface	Potash Brine-Sand Slurry	corrosion rate was explained by the combined effects of particle concentration and velocity. Due to the increased impact energy of the particles and the greater quantity of particles that impinged on the elbow surface, the increase in velocity and particle concentration intensified the extent of surface damage.
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2.1.5 Erosion of river bank bend

The study of erosive process of the river bend has been shown in Table 2.5

Table 2.5 Erosion Mechanism in river bend

S. No.	Authors and tool used	Study topic	Results
1	Uddin et. al, [37] 2012 used Acoustic Doppler Current Profiler (ADCP)	Flow and erosion at a bend in the braided Jamuna River	The rate of erosion of a particular Braided Jamuna River bend can be estimated using the analytical erosion prediction model.
2	Wang et. al,[38] 2019 used Laboratory Experiments	Experimental study of point bar erosion on a sand-bed sharp bend under sediment deficit conditions, Sedimentary Geology	Partial chute cut off may occur in the upper portion of the steep bend due to high discharge, hydrodynamic parameters of the point bar that are significantly lower in the lower portion and greater than those of the concave pool in the upper half.

2.1.6 General erosion rate papers

Field et al. [15] state that the effectiveness of swirl vortex devices is dependent on the settling characteristics of the suspended solids and the proportion of dissolved solids in the storm flow. When used appropriately in conjunction with other combined-sewerage controls or separately severed storm-water systems, splash vortex devices can play a critical

role in lowering combined sewer overflow and storm-water discharge pollution. The primary prerequisites for a trustworthy performance evaluation are precise sampling techniques, evaluations of suspended particles and other contaminants, and the distribution of influent and effluent settling velocities. Concurrent flow-rate measurement that is in sync with sample timings is also necessary. When applied as part of a full sewer system strategy rather than as a stand-alone solution, the swirl is a tried-and-true technique.

Li et al. [16], from a traditional perspective, following a time of operation, wear and ash deposition should be easily visible in the helically finned tube. Yet, based on observed phenomena and experimental data, it is discovered that the helically finned tube not only improves heat transfer but also has exceptional protection against wear and ash deposition. In comparison to the bare tube, both of these issues are significantly reduced.

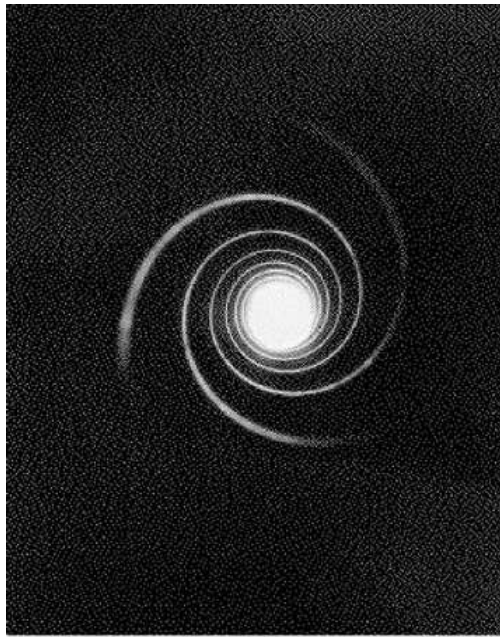
Li et al. [17] Axial flow pneumatic conveying (AFPC), a typical pneumatic conveying system, is frequently used in the dilute-phase regime in the high gas velocity sector. Because of things like particle degradation, pipe erosion, and power consumption, the conveying velocity needs to be kept to a minimum. Over the past 35 years, dense-phase pneumatic conveying has become more and more popular, leading to the development of several commercial systems. Unfortunately, these systems need significant pressure drops and are initially costly. Furthermore, dense-phase pneumatic conveying may produce unstable flows at low conveying velocities.

Li et al.[18] conducted an experimental investigation of the behaviour of particles in a horizontal diluted whirling flow pneumatic conveying system. Imaging approach has been used to measure particle velocities and concentration profiles. Li and Tomita introduced this innovative swirling flow approach, known as swirling flow pneumatic conveying SFPC., to a pneumatic conveying system in order to reduce power consumption, obstruction, particle degradation, and pipe wear. SFPC was found to be successful in the low velocity conveyance range. SFPC gas-particle two-phase flows, on the other hand, are a complex and unstable nonlinear dynamics system. Designing, optimizing, and running an SFPC system requires a thorough grasp of particle behavior.

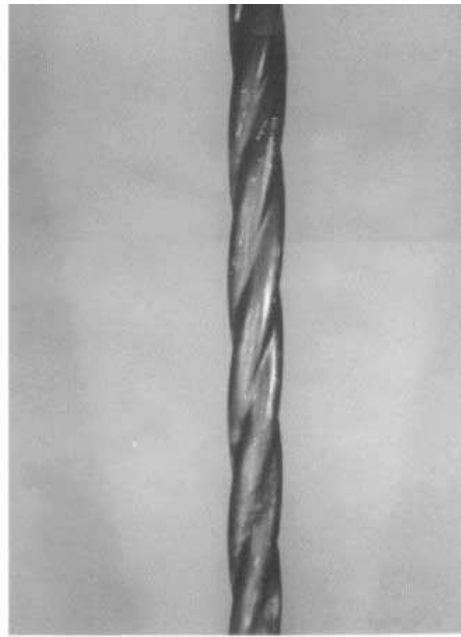
Wood et al. [19] have demonstrated that, in comparison to a traditional circular duct, pipes that promote swirl can get particles into suspension with reduced pumping power and pressure drop. By no means is this a novel concept. He enumerated the following benefits:

- Low minimum velocities were necessary to maintain particle solids in suspension;
- wear could be minimized due to the lower particulate velocities flows could be stopped and started without difficulty. At key locations, particle suspensions could be produced at a

fraction of the forward velocity needed in traditional systems. This might lessen both the overall erosive wear and the pumping power. Particle tracking modelling suspension flows via bend geometries with and without upstream swirl induction is done with computational fluid dynamics software. The swirling phenomenon is shown in Fig. 2.6, particle motion is shown in Fig. 2.7 and upstream flow in pipe bend shown in Fig. 2.8.



Interior axial view



Exterior longitudinal view

Fig. 2.6 Swirly flow boiler tube

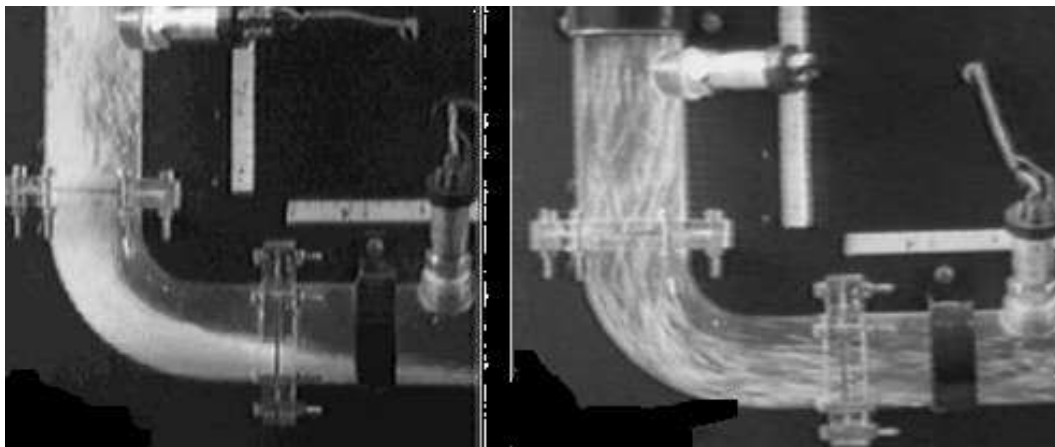


Fig. 2.7 The upstream swirl (right) effect on the particle dispersal in a bend [11]

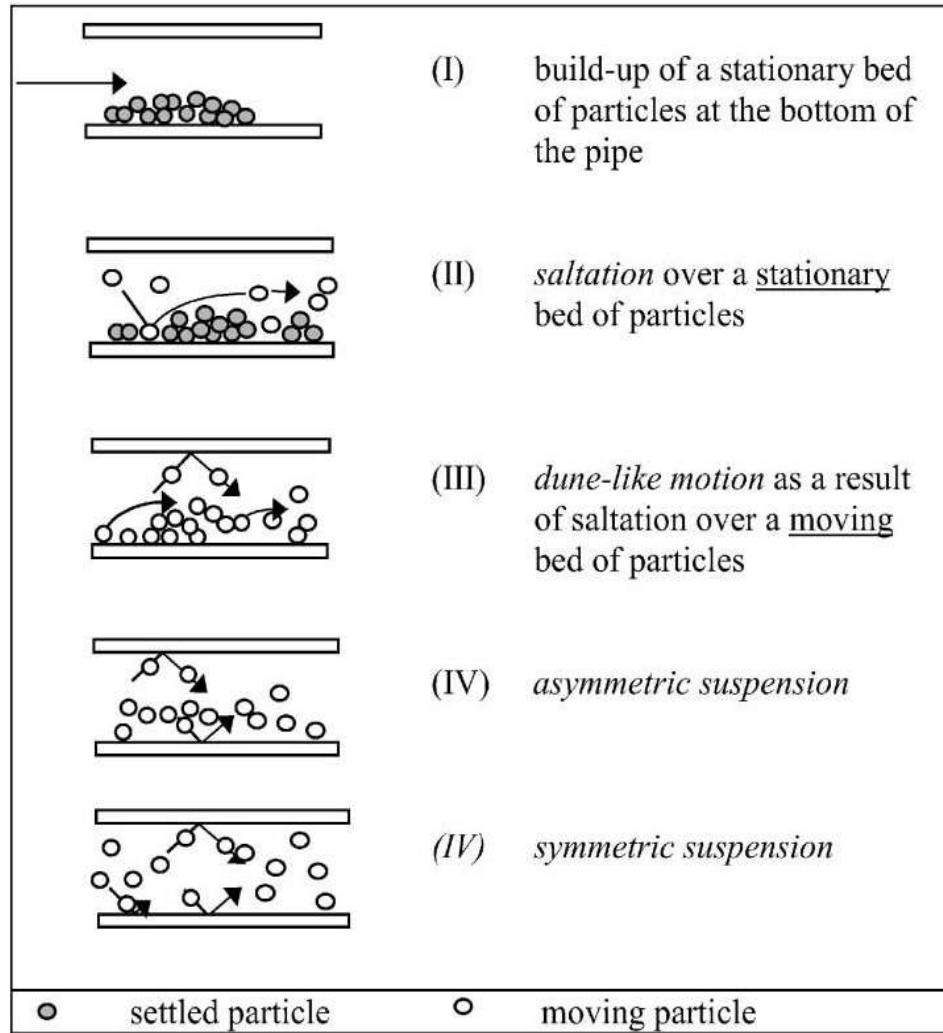


Fig. 2.8 Particle motion in swirling

Fokeer et al. [20] have previously provided a comparison between experimental data of the same configuration and the predictions from a computational fluid dynamics (CFD) model of flow in a three lobed helical pipe. Lean phase pneumatic conveying and heat transfer may benefit from the helical pipe's ability to boost axial velocities and create a swirl (or tangential) component in the flow field. Compared to traditional axial pneumatic conveying, swirl-inducing pipes have the advantages of lower conveying velocities, fewer pressure dips, and consequently lower power usage.

Chen et al. [58] have examined the volume of fluid (VOF) multiphase flow model in conjunction with the discrete phase model (DPM) to forecast the particle flow behavior in gas-liquid-solid multiphase flow across a vertical-horizontal elbow. Furthermore, the erosion behaviour of multiphase flow in the elbow is investigated using the Oka model. The Parsi et al. experimental results show good agreement with the projected degradation

rate and gas void %. Furthermore, the effects of liquid film, gas velocity, particle size, and particle mass flow rate on elbow erosion have been identified. The findings demonstrate that a liquid film serves as a buffer against erosion, slows down erosion, and increases particle resistance as well as size

Sun et al. [59] recommend adding rib structures to the inner wall of the bent portion. These structures are designed to improve transport efficiency and reduce wall wear by altering particle pathways and regulating the local flow field. The first stage is to use a connected CFD-DEM technique to assess the anti-wear performance of ribs with different forms. Next, under various combinations of trapezoidal rib widths and coverage angles, the flow characteristics, particle distribution, wear evolution, and energy consumption are methodically examined. An orthogonal experimental design is used to identify the primary contributing elements and the patterns associated with them. 120°), the rib structures perform remarkably well overall by greatly reducing the wear rate and particle guiding, hence increasing transport efficiency.

Chang et al. [60] investigated the mechanism underlying erosion caused by solid-liquid-gas multiphase flow in pipeline transportation. In CO₂ flooding schemes, pipeline oil passage is often accompanied by sand particles. The interplay of solid-liquid-gas multiphase fluid flow can occasionally cause significant erosion of pipeline inner walls, particularly in the vicinity of bends. The findings indicate that particle concentration and flow rates are the primary factors influencing erosion rates. Erosion mostly happens on the outside wall of curved pipes, with the highest rate of erosion being 1.539×10^{-2} kg/m

Gao et al. [61] demonstrated pipeline transportation is especially common in the chemical and energy industries. In order to minimize erosion wear on pipe bends, pipeline structure has a considerable impact on the properties of liquid-solid two-phase flow. The erosion characteristics of pipe bends with different bend angles of 60°, 90°, 120°, 135°, 150°, and 165° are investigated in this paper utilizing an Eulerian-Lagrangian approach with liquid-solid two-phase coupling. As the pipe bend angle increases, the high-pressure area on the inner outer wall of the pipe bend progressively decreases. The study's conclusions could, in theory, encourage the best pipe bend design in pertinent industrial fields.

Wang et al. [62] considered three significant affecting factors: the ratio of the intake to exit pipe diameters, the length of the variable-diameter section, and the roughness of the pipe wall. The impact of these factors on pipeline erosion and wear is investigated using a single-factor analysis approach. In particular, the Fluent software is used to carry out the required numerical simulations for variable diameter elbows with various morphologies. The results

demonstrate that as the inlet to output diameter ratio increases, so does the amount of wear on the pipe inlet and the outside wall of the elbow. When the diameter ratio exceeds 0.8, there is a noticeable increase in wear on the inner and outer elbow walls. Initially, the maximum erosion rate sharply decreases as the diameter ratio rises.

Yu et al. [63] examined the erosion of pipe bends caused by gas-solid two-phase flow at high pressure using dynamic mesh technology and the bidirectional fluid-structure interaction (FSI) approach. The effects of stress and wall deformation on erosion are simultaneously considered. In connection with the results of erosion prediction, three geometric parameters—bend radius, bend angle, and wall thickness—as well as working pressure and fluid velocity are investigated. Based on the findings of erosion prediction, a finite element model of a pipe bend with erosion faults is then built, and the collapse mechanism and buckling pressure of the pipe bend after a particular erosion period are investigated.

Pan et al. [64] have demonstrated that solid particle erosion in pipeline elbows is a persistent issue in the energy and process industries, where accurate but efficient prediction methods are much needed. processing fluid dynamics—discrete element method (CFD–DEM) simulations can produce high-fidelity erosion forecasts, but their processing demands severely limit their practical application. This work proposes a knowledge-informed reduced-order modeling approach that integrates proper orthogonal decomposition (POD) and Kriging interpolation to bridge this gap. It demonstrates how the enhanced POD–Kriging model can reproduce spatial erosion fields with accuracy and achieve speedups of over 2000×. Based on a surrogate, the proposed approach reduces prediction errors by up to 76% by traditional POD, with local errors in high-risk elbow regions being reduced to less than 4%.

Shirazi et al. [65] concentrated on erosion prediction and mitigation within blinded T-bends using numerical simulations. An erosion model based on monolayer energy dissipation was used to estimate erosion rates, and an Eulerian-Eulerian approach was used to represent the gas-solid two-phase flow. Numerical results were validated using experimental data. A parametric research was used to investigate the effects of air mass flow rate (0.025–0.07 kg/s), particle mass flow rate (1–3 kg/s), and blind end length ($L/D = 0.5, 1, 1.5$) on erosion. The results demonstrate a positive correlation between erosion rate and both air and particle mass flow rates, underscoring the need of optimal airflow conditions. However, it was found that increasing the blind end length reduced erosion.

Mu et al. [66] demonstrates predictions with Computational Fluid Dynamics (CFD) data, the hydrodynamic behaviour and erosion wear processes anticipated by Mu et al. [66] in a gas-solid two-phase flow pipeline system were fully investigated. First, by comparing the results of the CFD simulation with experimental data, the accuracy of the three erosion models—Oka, Vieira, and DNV—was confirmed. It was demonstrated that the Oka model was a better predictor of the multiphase flow in pipeline erosion occurrences. Second, the effectiveness and logic of ROM predictions were investigated, and patterns in erosion wear processes and hydrodynamic multiphase flow behaviours were discovered to be consistent with CFD findings.

2.2 Conclusions of literature review

The Conclusions of the illustrative literature review is explained below

- i. Researchers have attempted to minimize the erosive wear in pipe bends of pneumatic conveying pipe line.
- ii. Various concepts / techniques have been employed by the researchers for extending the life of pipe bends.
- iii. Thin strips/blades in pipes have been inserted for giving the motion (swirling) to particles lying parallel to the bend surface in order to avoid direct impact of particles at pipe bends.
- iv. Researchers have used CFD modeling to investigate erosive wear in different angles and geometries of bends.
- v. Researchers have analyzed every parameter to reduce erosive wear, as this wear will lead to a lot of expensive material.
- vi. A dearth of investigations has been seen for reducing wear of the pipe bends without inserting strips/blades in the pipeline.
- vii. Yadav et al. [44] used parameter as solid loading ratio=2, 1 bar air pressure inlet air velocity as 23.11 m/s and swirling speed as 35, 70 and 100 rpm and mean effective particle size as 125 μ m, 150 μ m and 2500 μ m on the basis of experience and literature.

2.3 Research gaps and motivation

After extensive literature survey it is found that:

- i. Researchers have carried various mechanism to induce swirl flow to reduce erosive wear in pipe bend but there is a need for investigation of self-powered swirling device.
- ii. There is a requirement of device to develop swirl flow instead of inserting tape, twisted tape etc.
- iii. Erosion corrosion combined study is required to be conducted on swirl flow.
- iv. Various researchers used different type of material but composite materials are required to be used to reduce erosive wear as jute fiber is used in pond to reduce erosion of sand.
- v. Mathematical modelling of swirling device is required to analyze the mechanism.
- vi. Optimization of motor operated swirling device is required to be done.
- vii. Problem of Choking of material in pneumatic conveying pipe line are required to investigate.
- viii. Various studies are carried out on the transportation of various materials, but cattle feed transportation studies are required to be done.
- ix. Bulletproof material to reduce erosive wear in the pipe bend should have some scope.

2.4 Research objectives

- i. To study erosive wear on different metallic samples under different operating parameters.
- ii. To develop a self-powered swirling device for modifying the particles' motion at pipe bends for reducing the erosive wear.
- iii. To perform Experiments and numerical investigations of erosive wear in pipe bends with and without a swirling device.
- iv. Researchers' literature is a pathfinder as well as a solution to present research. Researchers use experiments to find the bend erosion rate at different conditions and bend geometries. Researchers also used numerical prediction and simulation tools to find the results. Tools like CFX, CFD, RANS, etc. were used by researchers. To reduce bend erosion, swirling flow is the best method found in this literature review.

CHAPTER 3

EXPERIMENTAL SETUP AND RESEARCH METHODOLOGY

This Chapter cover research methodology used in this research, numerical prediction and experimental setup used for present research. The components and steps of CFD fluent discrete Phase modelling with governing equations are discussed in this chapter. All components of experimental setup and experimentation work are thoroughly explained in this chapter.

3.1 Research methodology

Based on the research Gap and research objective to reduce erosive wear in pipe bend following research, methodology has been planned to be used in this research:

- 1 To develop mathematical model and analyze the erosive wear at the bend.
- 2 To develop the experimental setup and the experiments will be carried out.
- 3 Valediction of experimental data with mathematical model.

In this research primary data is taken by performing different experiments and cfd numerical prediction and for model valediction in Ansys was performed by secondary data of researchers. The following research methodology was used in this research:

- 1 Experimentation
- 2 Numerical Prediction on Ansys
- 3 Comparison of both data

The flow chart of research methodology has been started from literature review and concluded with primary data of experiments and numerical prediction by cfd on Ansys. Until both data don't validate each other the loop will be continued. The diagram of flow chart is illustrated in Fig. 3.1.

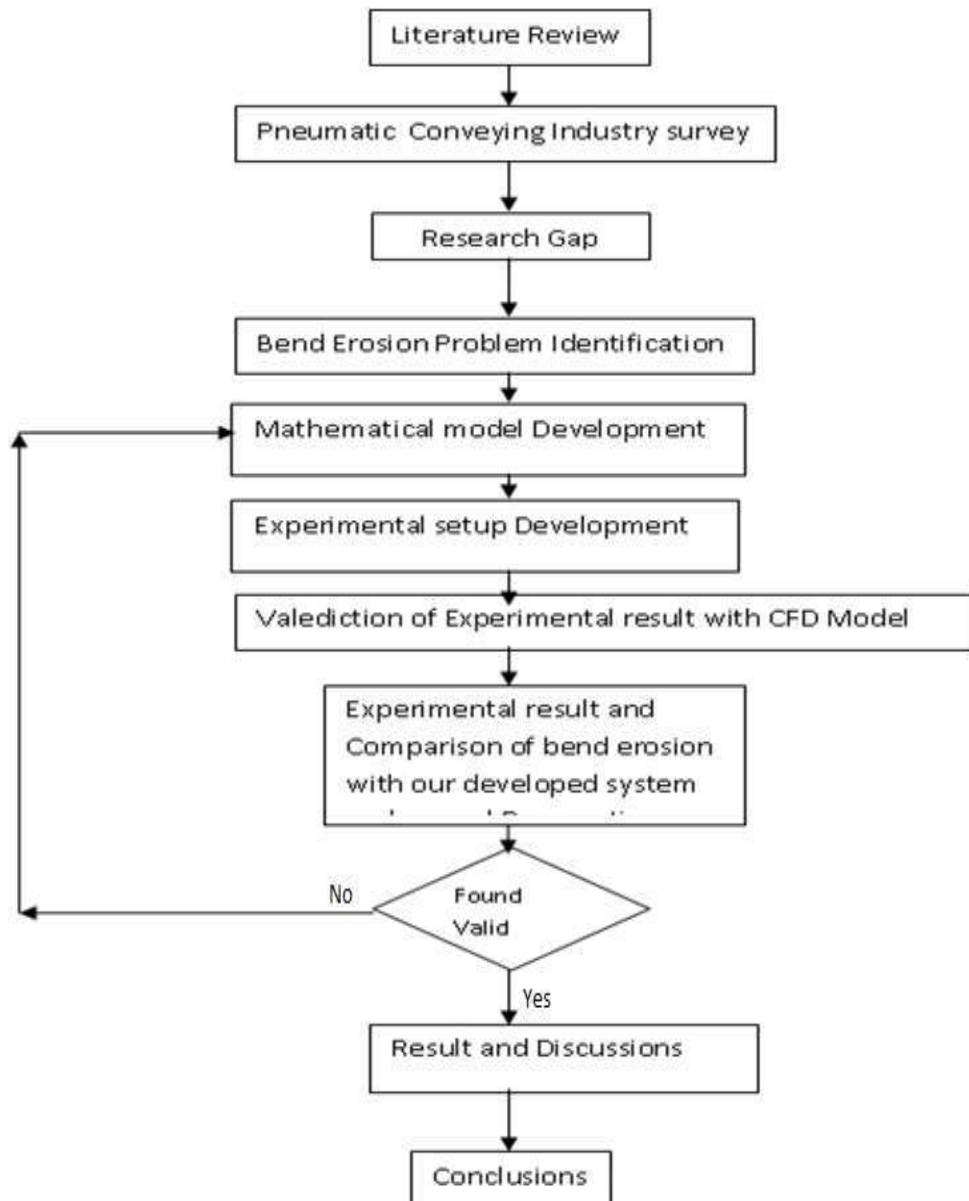


Fig. 3.1 Research methodology

3.2 Experimentation:

In Experimentation Following cases are taken in to consideration

- i. Characterization of wear in failed punctured bend
- ii. Bend erosion rate without swirling
- iii. Bend Erosion rate with motor operated swirling device
- iv. Bend erosion rate with auto swirling

3.2.1 CFD numerical prediction

CFD Numerical prediction was conducted on Ansys 2021 Discrete Phase Modelling (DPM). The following cases are Considered in numerical prediction:

- 1 Bend erosion rate without swirling device model
- 2 Bend erosion rate with motor operated Swirling Device model
- 3 Bend erosion rate with motor operated swirling Device at different bend angles model
- 4 Bend erosion rate with auto swirling Device model.

3.2.2 Simulation step of working

Step 1: -Identify the flow issue:

The basic step is used to identify the flow problem in CFD:

- To identify the purpose of the analysis of the pipe bend.
- To identify the easiest method to accomplish the bend erosion rate.
- To identify geometrical components that must be present for applying at the bend.
- To identify the operational and freestream constraints for the designed pipe bend.
- To Identify dimension of the spatial model (Axisymmetric, 1D, quasi-1D, 2D, and 3D) for pipe bend.
- To identify the pneumatic conveying required for cfd model.
- To identify temporal (Stable or erratic) modeling required for present model.
- To identify Flow (Turbulent, laminar, or inviscid) for CFD model
- To find fluid model for CFD analysis of flow in the pipe bend.

Step 2: - Design model for flow domain

In the process of conducting flow investigations, modeling plays a pivotal role as it involves the creation of a representation of the object on which the flow analysis will be performed. Typically, this entails the utilization of Computer-Aided Design (CAD) software to construct the geometric model. Depending on the complexity of the analysis, it may be necessary to introduce geometric approximations and simplifications. Furthermore, decisions are made at this stage regarding the dimensions of the finite flow domain, which will be used to simulate the flow. The boundaries of this flow domain partially coincide with the surfaces of the object's geometry. Additionally, specific surfaces are configured as permeable barriers, allowing the flow to either enter or exit the domain. The descriptions of the geometry and flow domain are commonly utilized as input for grid construction, a

vital component of the modeling process. Therefore, meticulous attention is dedicated to the structure and topology of grid generation to ensure the model's accuracy.

Step-3: - Set the boundary and initial conditions

Moreover, the iterative process in simulating flow within a finite domain is essential for conducting sensitivity analyses. It allows engineers to evaluate how changes in input parameters or boundary conditions impact the overall behavior of the system. By systematically adjusting these variables through iterations, one can gain a more comprehensive understanding of how the flow responds to different scenarios.

This sensitivity analysis is invaluable for identifying critical factors that significantly influence the flow dynamics and can guide decision-making processes. It provides the basis for optimizing system performance, making necessary adjustments to mitigate potential issues, and ensuring the design meets the required criteria. In essence, the iterative approach not only refines the simulation but also provides a platform for in-depth exploration and strategic decision-making in engineering and design.

Step-4: - CFD meshing

The process of grid generation in computational fluid dynamics involves several crucial steps. First and foremost, the structure and topology of the flow domain are defined, providing the blueprint for subsequent grid creation. This topological information guides the mesh generation process. Currently, the approach typically involves utilizing multi-block, ordered grids. These grids can vary in their arrangement, with blocks being positioned closely together, at a distance from each other, or even overlapping, depending on the specific requirements of the simulation. To ensure the accuracy and reliability of the grid, it must adhere to certain quality standards. These standards encompass criteria such as grid orthogonality, particularly along edges, relative grid stretching, grid skewness, and other factors vital to the simulation's fidelity. Additionally, the maximum spacing within the grid needs to align with the required resolution for critical aspects of the simulation. When dealing with boundary layers, special attention must be given to grid arrangements. The spacing of grid points near the wall and parallel to the surface is essential for accurately resolving boundary layer phenomena. In laminar sublayers of the boundary layer, the grid should extend deep enough to capture the relevant flow physics. For turbulent flows, it is crucial to ensure that the first grid point off the wall maintains a y^+ value below 1.0. This approach is necessary to accurately simulate the behavior of turbulent flows near solid surfaces.

Step-5: -Define simulation strategy for CFD

In the simulation approach, various critical decisions need to be made. These include the choice between space-marching and time-marching methods, the selection of an appropriate turbulence or chemistry model, and the careful consideration of which algorithms to employ. These choices significantly impact the accuracy and efficiency of the simulation, making them crucial aspects of the modeling process. Additionally, factors such as mesh resolution and boundary conditions also play a vital role in ensuring the fidelity of the simulation results. Therefore, a comprehensive understanding of these considerations is essential for successful fluid dynamics simulations.

Step-6: - Define the input files and parameters

The creation of an input data file containing the input parameter values associated with the selected strategy is a common necessity when utilizing CFD code. Furthermore, a grid file that includes grid information and boundary condition data is typically essential. The process also entails generating the grid itself and establishing the foundational flow solution files. These preparatory steps are crucial for setting up and running a successful CFD simulation, as they provide the necessary information and structure for the computational fluid dynamics code to work effectively.

Step-7: - Start the simulation

The simulation is conducted using a range of methods, encompassing interactive, batch, and distributed processing approaches. This diverse approach allows us to adapt our simulation methods to different scenarios and requirements, ensuring flexibility and efficiency in our simulation processes.

Step-8: - Monitor on the simulation's progress

The simulation process involves monitoring iterative convergence, aiming to achieve a "converged" solution. This ongoing assessment helps determine whether the simulation has reached a stable and accurate result. For more comprehensive information on this aspect, you can refer to the dedicated page titled "Examining Iterative Convergence," which provides in-depth details and insights into the convergence monitoring process during the simulation.

Step-9: - Do post-process the simulation to obtain the results

The post-processing phase not only ensures the extraction of meaningful data but also enables the visualization and representation of complex flow phenomena in a more understandable and interpretable manner. Through advanced visualization techniques and

data manipulation, engineers can gain a deeper understanding of how fluid dynamics impact the performance of various systems and components.

Moreover, the insights obtained from post-processing are instrumental in optimizing designs, enhancing efficiency, and making informed decisions to meet specific performance and safety criteria. In aerospace, for instance, it helps in refining aircraft and spacecraft designs, while in automotive engineering, it contributes to improving fuel efficiency and vehicle aerodynamics. In industrial processes, post-processing supports the optimization of manufacturing and fluid systems, ultimately leading to cost savings and improved product quality.

Step-10: Results comparison

After obtaining computed flow attributes through post-processing in a CFD simulation, the next step involves assessing the validity of these results. This assessment is typically done by comparing the computed data with information obtained from analytical models, computational research (such as other CFD simulations), or experimental measurements. This comparison serves as a crucial validation step to ensure that the CFD simulation accurately represents the real-world flow behavior and to verify the reliability and accuracy of the simulation results. It helps identify any discrepancies or areas where further refinement of the simulation model may be necessary to improve accuracy and confidence in the results.

Step-11: - Examination of sensitivity

It is essential to assess the sensitivity of the computed results to gain insights into potential discrepancies in result accuracy and computational performance concerning factors such as: Check the whole dimension, Check condition of CFD flow, Initially check all conditions, Check marching Problem, algorithms, mesh topology and mesh density, check turbulence model, Simple chemistry model, flux model, Numerical concept pertaining to CFD, boundary conditions, computer system. Additional details are available on the Verification Assessment and Validation Assessment pages.

Step-12: - Document

This comprehensive documentation allows for a clear and transparent account of the analysis, enabling stakeholders to understand the methodologies employed, the data gathered, the processes applied, and, ultimately, the results and their implications. It serves as a valuable resource for decision-making, peer review, and future reference in similar analyses. Additionally, it enhances the credibility and reproducibility of the work, contributing to the overall trustworthiness of the findings.

3.2.3 CFD governing equations:

Viscous -SST K-omega

One of the most widely used and justified turbulence models in industrial CFD is the Shear Stress Transport (SST) variant, which offers superior accuracy for wall-bounded flows—especially those with unfavourable pressure gradients and separation—while maintaining computational efficiency. For RANS (Reynolds-Averaged Navier-Stokes) simulations, it is the industry-standard "jack-of-all-trades" since it combines the best aspects of the model (precision of the near wall) and the model (robustness of free-stream)

Derivation of Viscous -SST K-omega model equation is shown in appendix 1.

The Shear Stress Transport (SST) turbulence model, developed by Mentor in 1993, is a widely applied two-equation eddy-viscosity model. It was formulated to improve the accuracy of turbulence prediction by combining the strengths of existing models. The k- ω portion of SST offers dependable low-Reynolds number performance by resolving the near-wall flow directly, thus eliminating the requirement for additional damping functions. A notable advantage of this model is its ability to capture flow behavior up to the wall, including the viscous sublayer, addressing a major drawback of conventional k- ϵ models, which are highly influenced by inlet turbulence conditions. In the free-stream region, the SST formulation transitions smoothly to k- ϵ behavior, allowing more reliable predictions for cases involving strong pressure gradients and flow separation. It's crucial to remember that the SST k-model may show a modest tendency to generate considerably larger turbulence levels in situations with high normal strain, such as stagnation and rapid acceleration. However, in contrast to a conventional k-model, this trend is significantly less pronounced. The scientific community's broad acceptance and use of the SST k-model demonstrates how well it works to handle a variety of turbulent flow scenarios. Governing equations are demonstrated from 3.1 to 3.8

Kinematic Eddy Viscosity

$$\nu_T = \frac{a_1 k}{\max(a_1 \omega, SF_2)} \quad (3.1)$$

Specific Dissipation Rate

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (3.2)$$

Turbulence Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right] \quad (3.3)$$

$$F_2 = \tanh \left[\left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right) \right]^2 \right] \quad (3.4)$$

$$P_k = \min \left(\tau_{ij} \frac{\partial U_i}{\partial x_j}, 10\beta^* k \omega \right) \quad (3.5)$$

$$F_1 = \tanh \left\{ \left\{ \min \left[\max \left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right), \frac{4\sigma_{\omega 2} k}{C D_{k\omega} y^2} \right] \right\}^4 \right\} \quad (3.6)$$

$$C D_{k\omega} = \max \left(2\rho\sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right) \quad (3.7)$$

$$\phi = \phi_1 F_1 + \phi_2 (1 - F_1)$$

$$\alpha_1 = \frac{5}{9}, \alpha_2 = 0.44$$

$$\beta_1 = \frac{3}{40}, \beta_2 = 0.0828$$

$$\beta^* = \frac{9}{100}$$

$$\sigma_{k1} = 0.85, \sigma_{k2} = 1$$

$$\sigma_{\omega 1} = 0.5, \sigma_{\omega 2} = 0.856$$

3.2.4 Discrete phase modelling:

The Euler-Lagrange method is used in modelling to control the discrete phase. This method treats the fluid phase as a continuous medium during the solution of the Navier-Stokes equations and tracks individual particles as they travel through the projected flow field, concentrating on the dispersed phase. As mentioned in reference [57], it is important to note that mass, energy, and momentum can be exchanged between the fluid phase and the dispersion phase. The use of sand in the discrete phase of this study has certain characteristics, such as a particle diameter of 1000 μm , a density of 2500 kg/m^3 , and a flow rate of 0.1 kg/s . We use a non-spherical drag rule, as explained in the same reference [57], to take into consideration the non-spherical shape of these sand particles.

Sand with particular characteristics, including a particle diameter of 1000 μm , a density of 2500 kg/m^3 , and a flow rate of 0.1 kg/s , was employed in this study's discrete phase. We use a non-spherical drag equation, as explained in the same reference [57], to account for the non-spherical shape of these sand particles. Equations are written from 3.1 to 3.14

where: C_D represents the drag coefficient and Re_D the Reynolds number.

$$C_D = \frac{24}{\text{Re}_D} \cdot (1 + b_1 \cdot \text{Re}_D^{b_2}) + \frac{b_3 \cdot \text{Re}_D}{b_4 + \text{Re}_D} \quad (3.8)$$

The values for the b_1 , b_2 , b_3 and b_4 coefficients are calculated as follows:

where:

ϕ stands for the form factor,

S is the actual surface area of the particle, while s is the surface area of a sphere with the same volume as the particle.

For the CFD analysis, a sand particle form factor of $= 0.9$ was chosen.

$$b_1 = \exp(2.3288 - 6.4581\phi + 2.4486\phi^2) \quad (3.9)$$

$$b_2 = 0.0964 + 0.5565\phi \quad (3.10)$$

$$b_3 = \exp(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3) \quad (3.11)$$

$$b_4 = \exp(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3) \quad (3.12)$$

$$\phi = \frac{s}{S} \quad (3.13)$$

3.2.5 Uncertainties and errors in CFD

Uncertainties and errors in CFD are concentrated on the grid convergence index as the main tool in our arsenal to manage and quantify uncertainties. Using a series of 3 grids, and a quantity of interest such as the lift or drag coefficient, it can calculate how much uncertainty in the measurement of that quantity on grids. Contrary to common belief, the grid convergence index is not a measure to establish the accuracy of our simulation; instead, it only specifies how much precision we have in measurements of key quantities of interest in our solution. This means that we may get an accurate result, even if a relatively high grid convergence index, but the uncertainty in this measurement is high, i.e. our confidence in the precision is low and thus, even though we may see an accurate result, it may be a fluke. In this case, comparison against experimental data is essential. While the grid convergence index does not provide us with a measure for how accurate our simulations are (if life was only that easy), it does present one of the best chances we have to gain confidence in our simulations. In some areas, it is an essential piece of evidence to gain trust in simulations and in the absence of any experimental data or high-fidelity numerical simulation data, it may be best chance to establish confidence in the results.

3.3 Experimentation setup

A setup for experimentation was established to find the erosion rate with swirling and Without Swirling. Cases taken in experimentation and CFD numerical prediction are as follows:

Case 1: Wear Characterization of eroded bend.

Case 2: Bend Erosion Experiment performed with Auto Swirling Device.

Case 3: CFD Numerical Prediction on Ansys Software with data validated by literature.

3.3.1 Steps followed in Experimental Setup: -

This complete research is carried out to reduce erosive wear in the pipe bend. CFD numerical prediction and experimentation were performed to reduce the erosive wear in a mild steel pipe bend. Many steps are taken to perform this research.

3.3.2 Experiment Setup for Swirling Device

1. Test Plant

A Pneumatic conveying pilot plant has been used for investigation of swirling device. Sketch of pilot plant is shown in Fig. 3.2 The test plant has a low-pressure blow tank with a rotary feeder, which is used to feed material into the pipeline. A storage hopper is used with butterfly valve attachment to feed material contained in blow tank. The same storage tank was used to collect material from return line. Bag filters were mounted above the storage hopper that separates air and material on discharge from return line. The storage hopper is fitted with three equally spaced load cells at 120° apart. The load cell is used to record material flow rate. A nozzle bank consisting of choked flow, convergent divergent nozzles were used to control and measure air flow rate to blow tank as well as to conveying line. Pressure gauges are mounted to record conveying line pressure drop and blow tank pressure. A two-stage root blower was used for compressing air into pipeline. The test loop in pilot plant is 40 m long and has an internal diameter of 51mm. The whole setup was built in horizontal floor. The distance between the bends was kept at 5 m or more which was sufficient to reaccelerate the particle back to its terminal velocity.

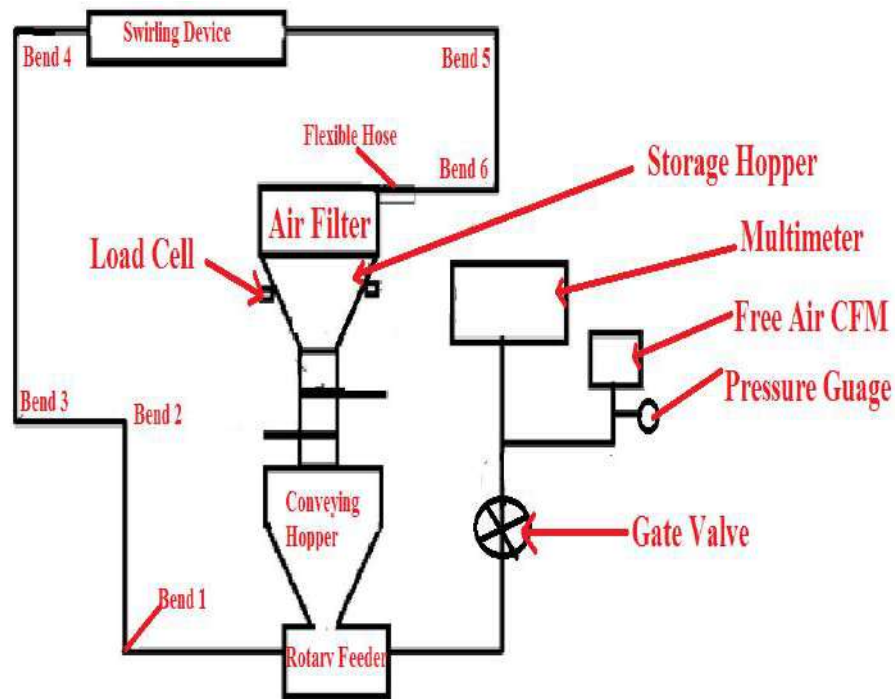


Fig. 3.2 Systematic Diagram of Pilot Plant [44]

In Fig. 3.3 complete pneumatic conveying plant is shown. Material is loaded in the storage hopper having capacity to store 400 kg of silica sand and through butterfly valve same material transferred to blow tank hopper where root blower is attached to mix silica sand with air and rotary feeder provides the feed rate. After that silica sand was conveyed from pipes and bends and again get back in to storage hopper where filter separated air and powdered material.

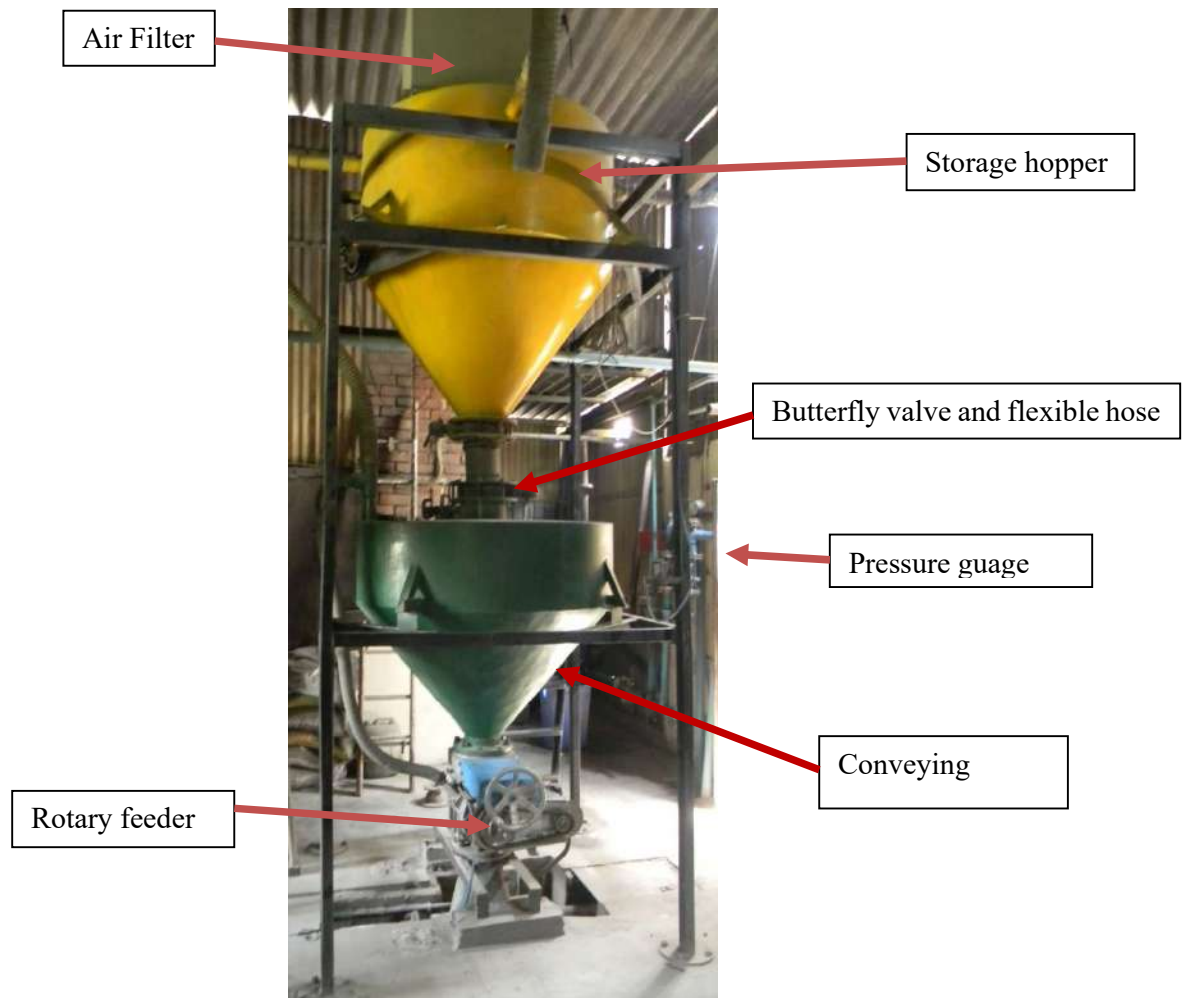


Fig. 3.3 plant Photograph [44]

In Fig. 3.4 at 120° three Load cells are attached to measure the load of recirculated silica particles. The data of load cell define cycle completion.



Fig. 3.4 Storage Hopper with three load cells 120 degrees apart [44]

In Fig. 3.5 double stage rotary root blower is shown in this root blower one suction silencer and one discharge silencer is used suck the air from atmosphere and discharge air to blow tank. Rotary blower is operated by motor and belt pulley arrangement.



Fig. 3.5 Root Blower [44]

In Fig. 3.6 shows pressure gauges and flow meters in pipelines of pneumatic conveying. 51mm inside diameter pipeline is used for conveying the silica sand.



Fig. 3.6 Pressure gauges [44]

3.3.3 Modification of test plant: -

In Fig. 3.7 Motor operated swirling device with modified pipeline of 40m length with different bend locations is shown. Erosive wear readings are taken with and without swirling device. This modification is illustrated shown in Fig. 3.7

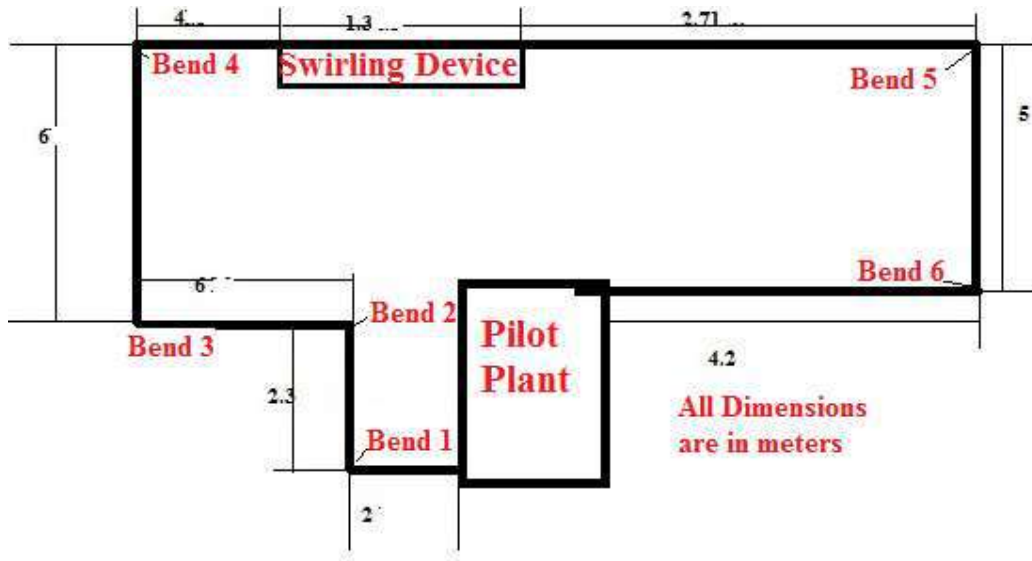


Fig. 3.7 New loop for modified plant for swirling device [44]

In Fig. 3.8 motor operated swirling device is shown where 1500mm of pipe was rotated with the help of gear motor with belt pulley and gear arrangement. Leakage at the mating end of rotating pipe was arrested by labyrinth seal. Pillow Block of 513 are used to support and retain the assembly.

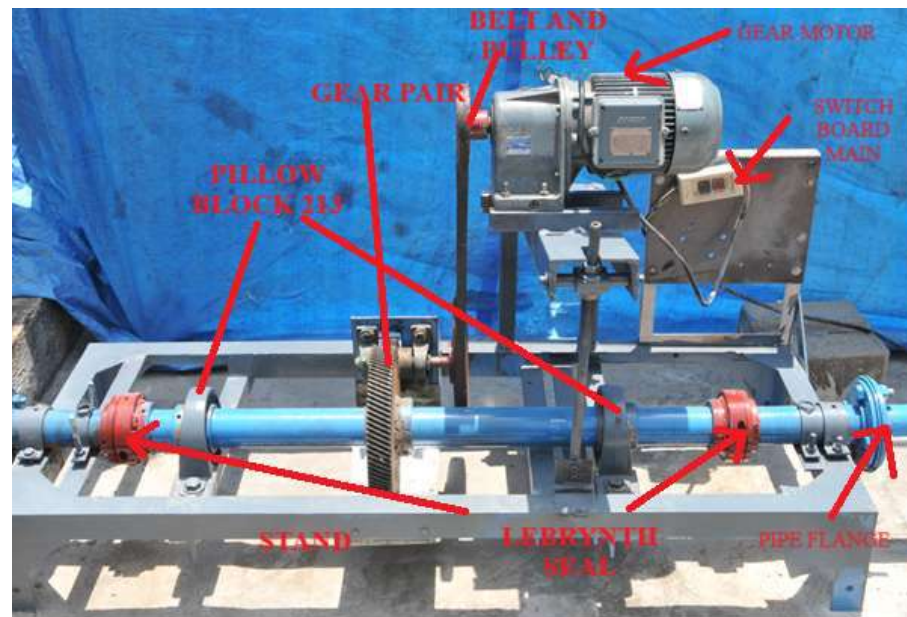


Fig. 3.8 Motor operated Swirling Device [44]

3.3.4 Development of auto swirl device

Auto Swirling device is made with hand blower, labyrinth seal, two pillow bocks, two bend and auto swirl pipe are discussed.

Conveying Hopper: Hopper with a capacity of 10 kg sand particle is attached with manually controlled flow rate valve shown in Fig. 3.9. After this closed hopper feed control valve a T type attachment is also used to mix air with silica sand.

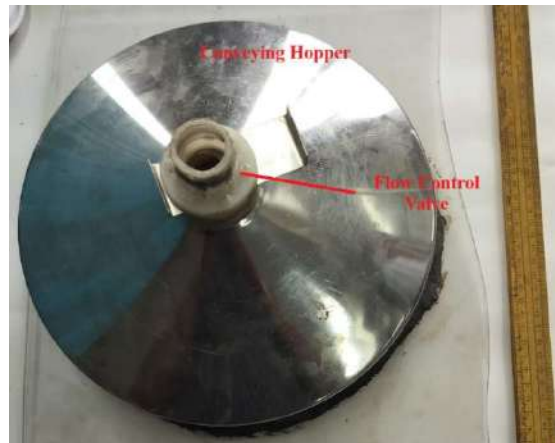


Fig. 3.9 Conveying Hopper With Flow control attachment

Hand/root Blower is shown in Fig. 3.10 is used to transport particles from one place to other is fitted with bend attachment Hand blower technical specifications are as follows: - Voltage=220 Volt, Power=1000W, Air speed=270 km/h, Airflow=120 m³/h (4.5 m³/min) no-load speed: 16000 rpm), Weight: 2.25 kg, Run Time 10 minutes nonstop, Pressure; 1 Bar (Atmospheric Pressure). These parameters are also used to find bend erosion rates.



Fig. 3.10 Root blower

Mild steel pipe bends are used to calculate erosion rate in pipe bend shown in fig 3.11. Bend dimensions used as per the literature are 51mm inside diameter, 60 mm outside diameter, 4mm wall thickness, and GI-coated bends purchased from the market are used in the auto swirl device. Bend without swirling, one side socket is attached for fitting, and the other side is attached for hopper fitting and blower attachment.



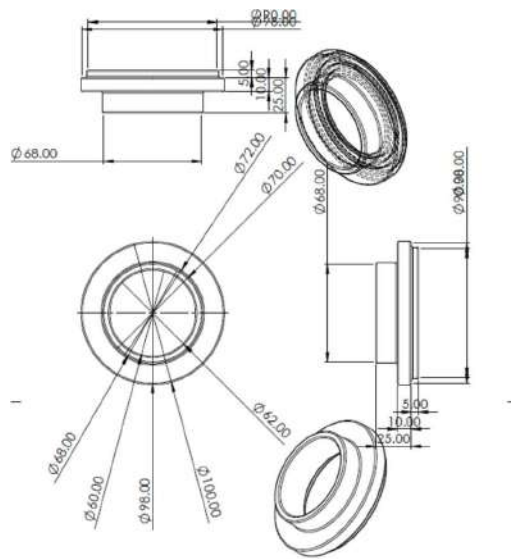
Fig. 3.11 Bends of auto swirl device

Labyrinth Seal is used to provide free motion of the pipe for auto rotation, it should be free at both ends. Labyrinth seal provides the free motion as well as prevents the leakage of material in the free space, as shown in Fig. 3.12. Alloy steel EN24 material was used for fabrication of labyrinth seal for the motor operated swirling device.

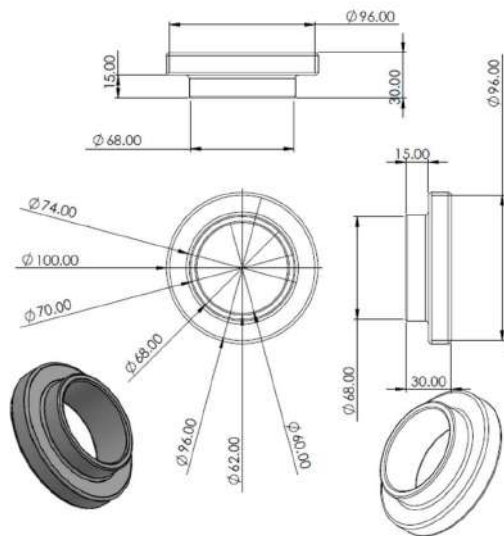


Fig. 3.12 Alloy steel EN24 metal Labyrinth seal

In Auto swirling device metal labyrinth seal wasn't used because of heavy weight hence Labyrinth Seal made of PLA material was used. Metal seals have higher weight hence it increases the drag force on the auto swirler, so seals are designed and made on 3 D printer. Solid works Drawing of Labyrinth seal female and male part are shown in Fig 3.13. STL file on 3D Printer is shown in Fig.3.14 this seal had only 130 grams' weight and this complex drawing is easily made by 3D printer. Due to tolerance issues these seals are not used and solid bush bearing was used in auto swirling devices. Drawing of metal seal and PLA seal are same shown in Fig 3.13.

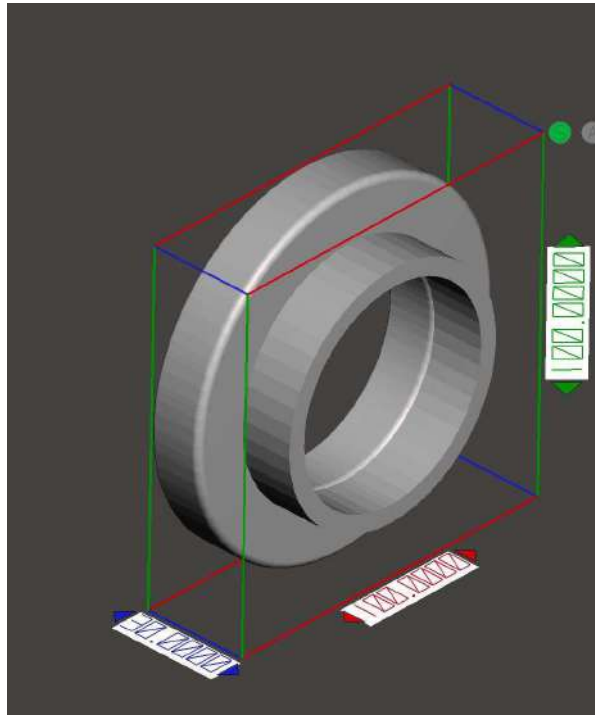


a. Labrynth Seal Female Part drawing

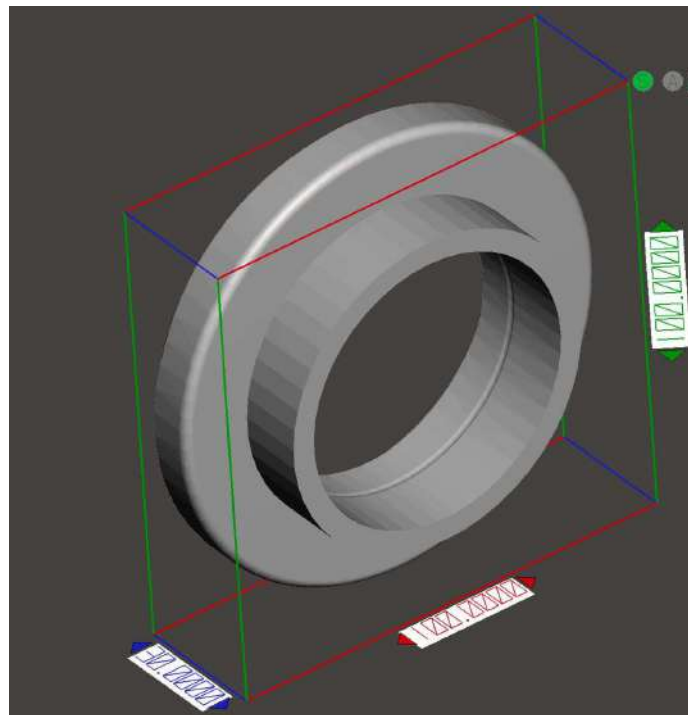


b. Labyrinth seal Male Part drawing

Fig. 3.13 Labrynth Seal drawings



Male part



Female part

Fig. 3.14 3D printer STL file of male and female part of Labyrinth seal

Auto Swirler Pipe: This Pipe was designed in Autocad three swirl blades are designed with 120° Swirl angle and this complex geometry was created on 3 D printer with Poly Lactic

Acid (PLA) material. This pipe weight was 64 grams, and its length was taken as 200mm. Shown in Fig. 3.15. In fig.3.16 Auto swirler STL file on 3D printer and 3d printed swirler is shown.

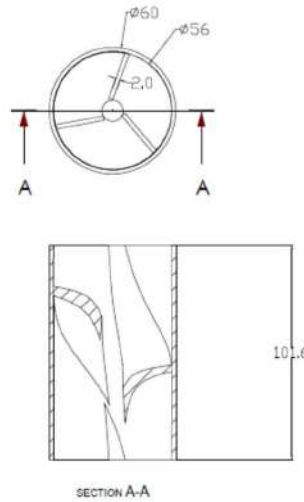


Fig. 3.15 Auto Swirler Drawing

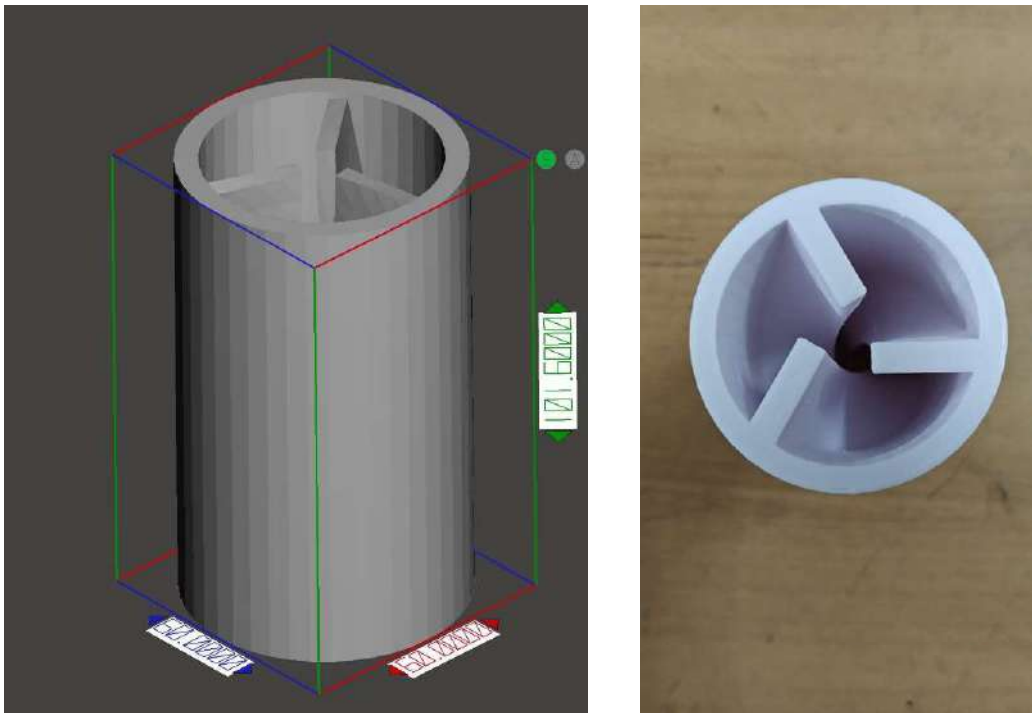


Fig. 3.16 Auto Swirler STL file and final 3D Printed file

Assembly of Auto Swirler: the complete assembly of auto swirler is shown in Fig. 3.17. in this assembly root blower fitted with sand hopper inlet and outlet bend Bushes and swirler is clearly shown.



Fig. 3.17 Autoswirl assembly

Weighing Machine: Weighing Machine was used to find out the weight loss due to erosion. Before experiment and after conveying 100 kg of material weight loss taken to calculate weight loss due to erosion shown in Fig. 3.18.



Fig. 3.18 Weighing Machine measured Bend weight.

3.3.5 Development of Auto Swirling Device with Swirl blades:

Firstly, Auto swirler was made with mild steel Pipe with profile blades tightened by screw the concept was taken that in case of erosion of blades those can be changed but limitation

in that system was found that pipe was not rotating due to heavy weight. Reduction in erosive wear was reported due to swirl flow induced by profile blades shown in Fig. 3.19.

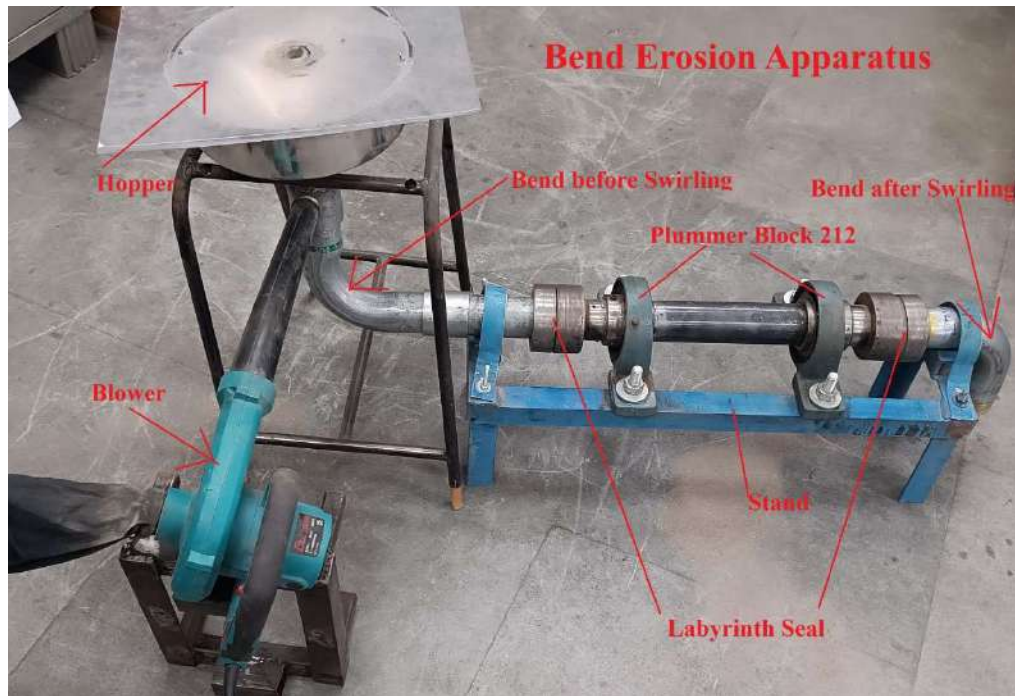


Fig. 3.19 Bend erosion apparatus

3.3.6 Sieve Analysis Apparatus:

During Experimentation silica sand particles degraded with recirculation of same. To calculate Mean effective Particle Size (mep) we require sieve analysis apparatus. It contains different size of Sieves and 100 gm of weight of silica sand taken and after that all sieves placed on each other and complete assembly mounted on the vibrator after shaking from all sieves weight %age in each sieve calculated and that data shows mep (mean effective particle size. In Fig. 3.20 different types of sieves which were used during experimentation are shown.



Fig. 3.20 Different types of sieves

In Fig. 3.21, sieve arrangement of different sizes of sieve shown from 212-micron size sieve to 63-micron size sieves were used to calculate mean effective particle size.



Fig. 3.21 Sizes of sieve

In Fig. 3.22, the apparatus to separate the material from different sieves is extracted by a motor-operated vibrator.

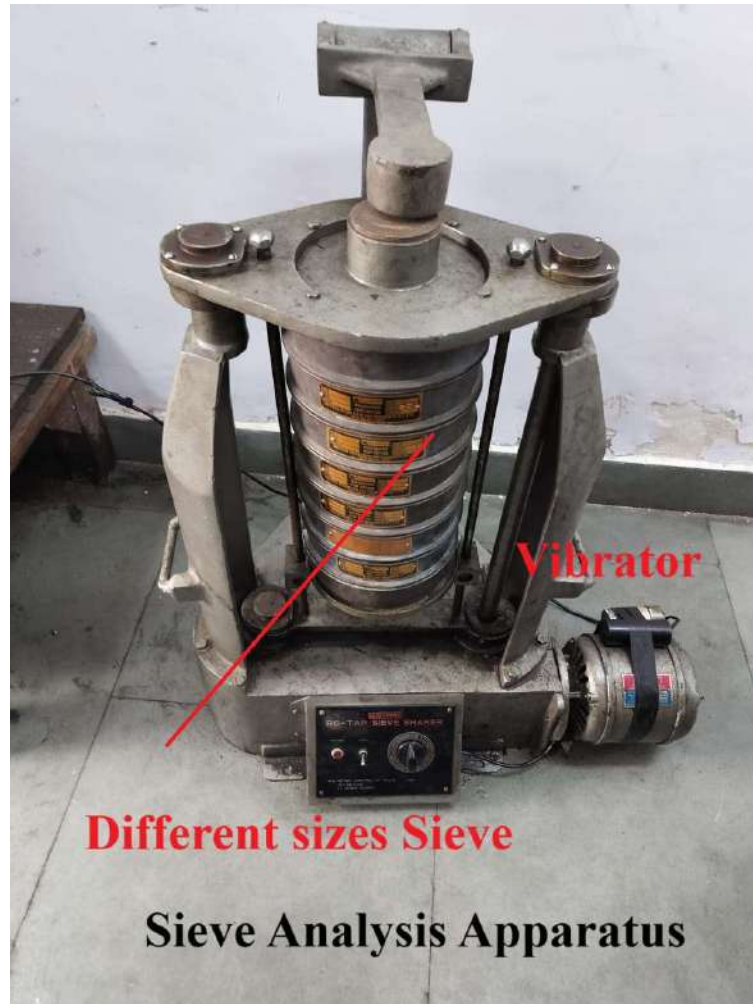


Fig. 3.22 Sieve Analysis Apparatus

3.3.7 Pin on Disc (POD) Tribometer

Pin on Disc machine shown in fig. 3.23 was used in failure characterization of failed bend are taken and abrasive wear with different size emery paper was calculated. The pin-on-disc wear test is a tribological test method used to evaluate how materials wear under sliding contact. By allowing a stationary pin or ball specimen to glide across a rotating disc, researchers can investigate wear mechanisms and material performance. The test is conducted with controlled parameters like load, speed, and temperature and can be run dry or lubricated. POD had LVDT sensors to calculate wear and friction.

In this chapter research methodology of numerical analysis and experimental performance was adopted. Steps in numerical prediction by CFD discrete phase model from identification of problems to documents preparation was followed in this research. Experimental setup components of motor operated swirling device and auto swirling device are step by step discussed with their performance parameters. The governing equations for k omega sst ansys cfd dpm model are explained to find erosion rate. This chapter shows the development of auto swirler with drawing is shown which was printed on 3D Printer. In experimental setup easy assemble and disassemble applications are used to perform experiments. Pin on disc tribometer was also used to find abrasive wear results.

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

In this chapter, experimental results of without swirling device, motor operated swirling device and auto swirling device were compared and tabulated to compute results. CFD results of without swirling device, motor operated swirling device and auto swirling device were compared and tabulated to compute results.

4.1 Experimental results

Experimental results are categorized into three cases:

- i. Bend Erosion Without Swirling Device
- ii. Bend erosion with swirling device
- iii. Bend erosion with auto swirling Device

4.1.1 Results of pin on disc

The pin is made up of Bend Material mild steel and Disc is made up of Emery Paper of different sizes. wear test Input and output parameters, and their levels are shown in Table 2. On Minitab Software these results are analyzed by Taguchi L9 array results are shown from Table 4.1 which shows as abrasive particle increases specific wear rate increases.

Table 4.1 Wear test parameters and their levels

Parameters			Experiment Results	
Abrasive Particle Size μm	Sliding Velocity m/sec	Load (N)	COF	Specific Wear Rate mm^3/Nm
200	3.14	10	0.380	0.09230
200	6.28	20	0.406	0.12300
200	12.56	30	0.421	0.13100
160	3.14	20	0.395	0.10190
160	6.28	30	0.411	0.12070
160	12.56	10	0.367	0.08503
125	3.14	30	0.401	0.11100
125	6.28	10	0.350	0.07960
125	12.56	20	0.360	0.09820

In Fig. 4.1 emery paper 80 wear impression after POD experiments is shown different tracks were used to find results. Those tracks wear were clearly visible.



Fig. 4.1 POD wear impressions on emery 80

In Fig. 4.2 emery paper 100 wear impression after POD experiment are clearly shown on the periphery of track diameter.

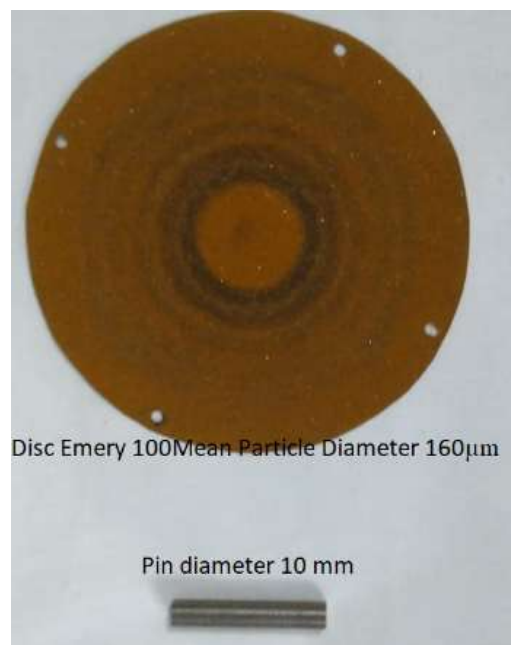


Fig. 4.2 POD wear impressions on emery 100

The abrasive material nearly wears out and significant wear of pin was observed in very less operating time.

In Fig. 4.3 emery paper 120 wear impression after POD experiments is shown. In this photograph impressions are clearly visible.

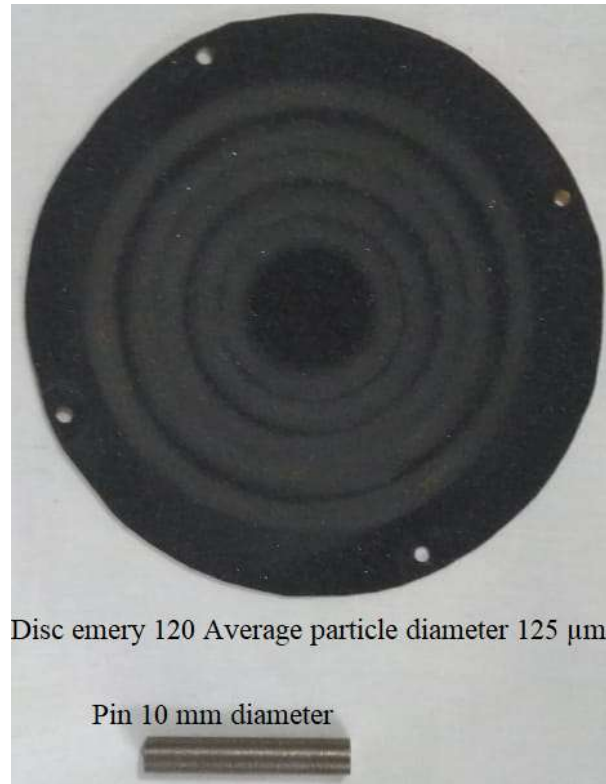


Fig. 4.3 POD wear impressions on emery 120

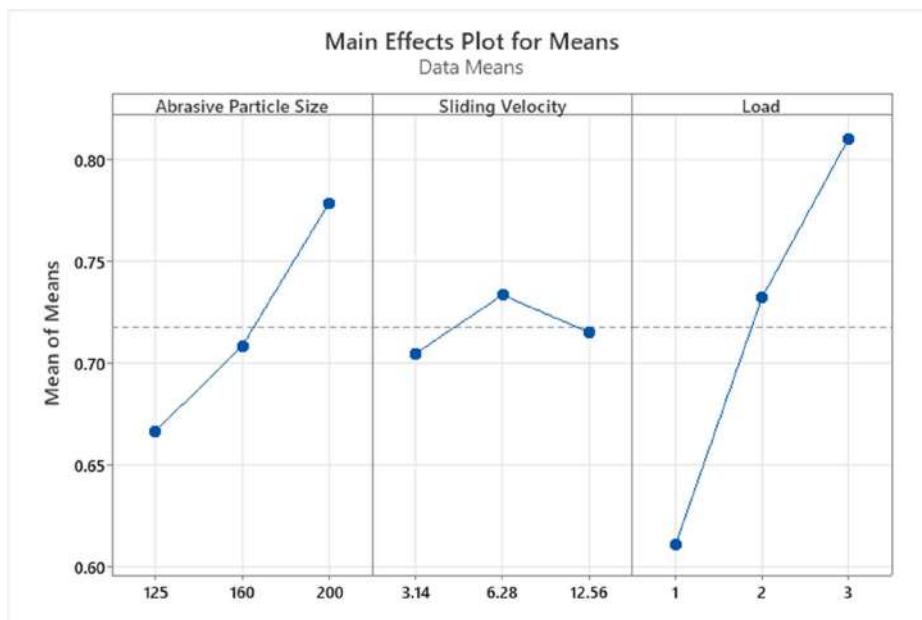


Fig. 4.4 Plots of means

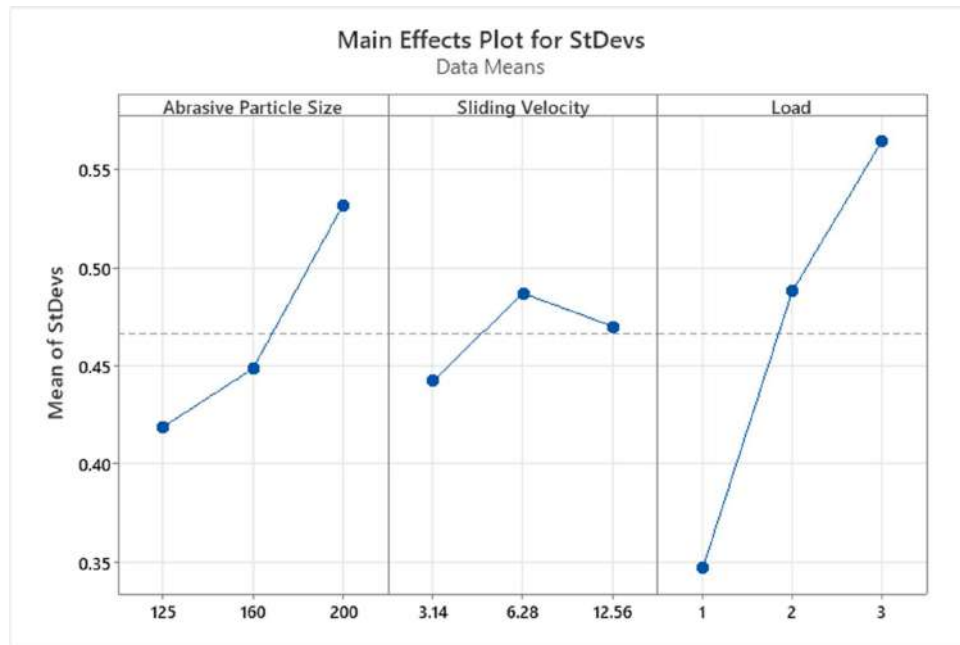


Fig. 4.5 Standard Deviation Plots

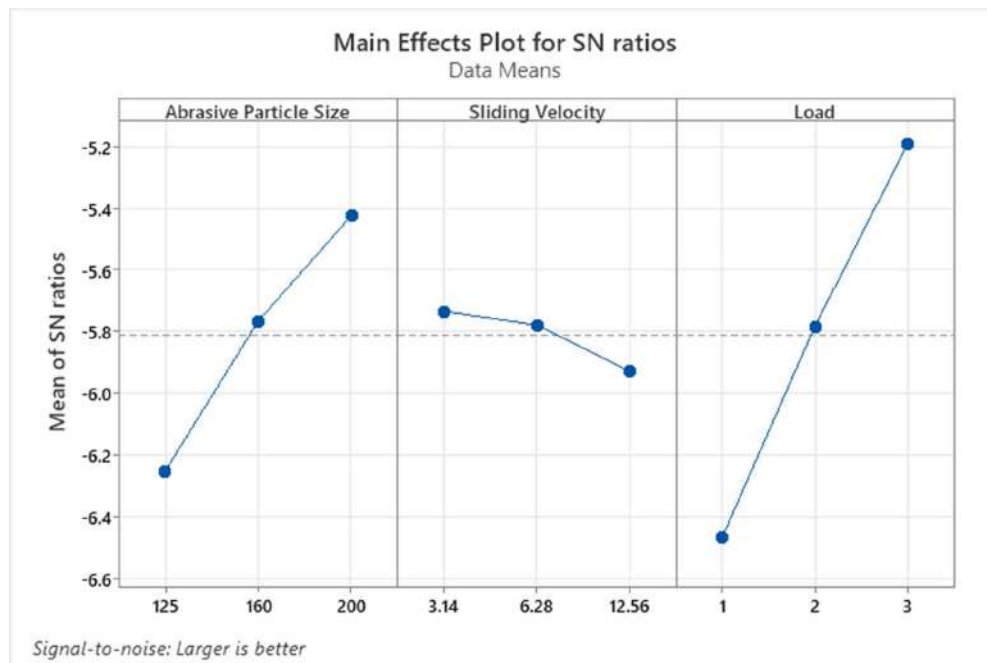


Fig. 4.6 Main Effects Plot of SN ratios

Taguchi Design L₉ array results were shown in graphs Fig. 4.4, 4.5 and 4.6 above. Various data generated for standard deviation, means and S. N. ratios and results are computed. Out of three statistical equations [56], the two equations are employed for the smaller the better Eq. 4.1, and the larger the better Eq. 4.3.

$$\text{Smaller the better} = -10 \log \Sigma(Y^2) / n \quad 4.1$$

$$\text{Nominal the better} = 10 \log \Sigma ((Y^2)/\sigma^2) \quad 4.2$$

$$\text{Larger the better} = -10 \log \Sigma ((1/Y^2)/n) \quad 4.3$$

where, Y observed value for the specified factor level Combination, n Number of responses in the factor level Combination, σ Standard deviation of the responses for all noise factors for the specified factor level combination. These graphs are taken for smaller the best as wear rate should be less will be helpful for sudden damage. Above shown figures and tables shows the various characterization of load, Specific wear rate, with Different Emery papers on coefficient of friction. These graphs concluded that wear increase with increase in abrasive size of material.

4.1.2 Test on ultrasonic thickness gauge: -

In this experiment, test method - Ultrasonic thickness gauge model - UTM-9 and calibration block - 4.0mm metal erosion is gradual converted on length of nearly 10mm (4") on either side of pipe bend from eroded hole. The thickness of bend eroded from 3.8 mm to 0 mm means punctured place shown in Table 4.2.

Table 4.2 Loss of Thickness due to erosion on Ultra Sonic thickness gauge

Loss of Thickness Due to Erosion			
Distance from the eroded point (mm)	Thickness at that point (mm)	Distance (centre) (mm)	Thickness puncher (mm)
95 mm	3.8 mm	10 mm	2.4 mm
80 mm	3.4 mm	25 mm	3.3 mm
50 mm	2.6 mm	35 mm	3.3 mm
25 mm	2.1 mm	50 mm	3.4 mm
15 mm	1.4 mm	80 mm	3.5 mm
Puncture 0 mm	0mm	100 mm	3.8 mm

4.1.3 Microstructure study: -

Test piece taken out from eroded zone of pipe bend finely polished, on 3% nital etch, at 100x, matrix reveals pearlitic in ferritic matrix & grain size 7 measured ASTM E-112 shown in Fig 4.7

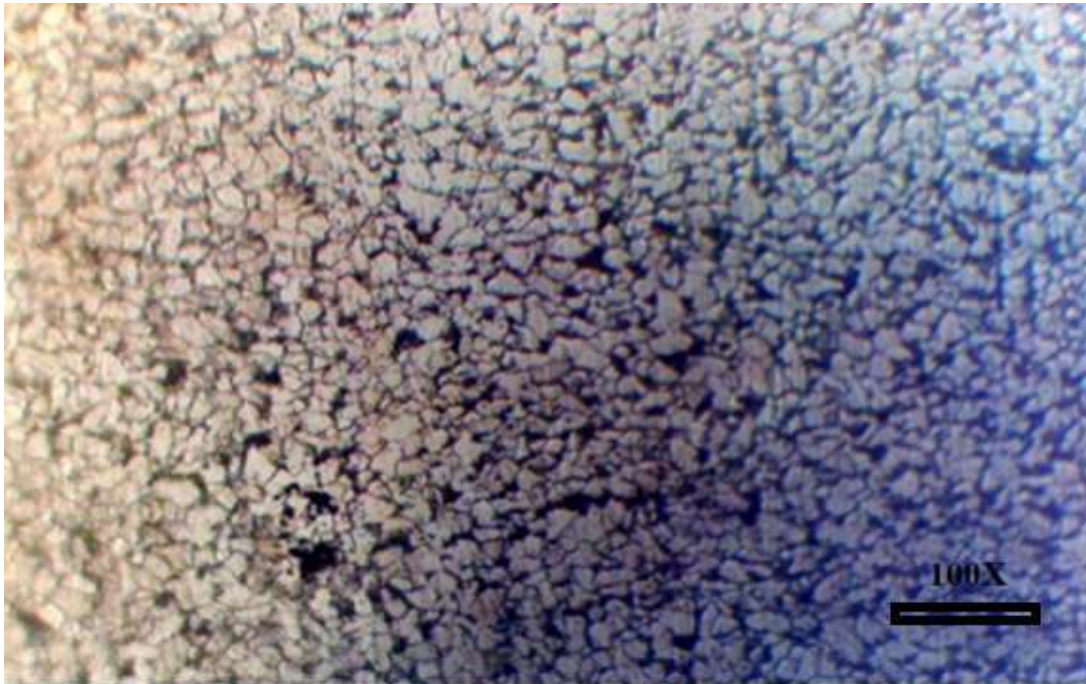


Fig. 4.7 Microscopic View of Bend Punctured section

4.1.4 Macro examination: -

Cut Section Etched in 50% hot hydrochloric acid for 25-30 Minutes at 70-80°C Observation. On macro etching sheet used to make steel pipe / bend is of duplex nature making more vulnerable at the core of the width of pipe thickness may be response for metal erosion shown in Fig 4.8.



Fig. 4.8 Macroscopic examination specimen

4.1.5 Hardness test: -

Hardness test HRBW 77 and HRBW 78. But it still gets eroded due to bombardment of tiny particles on the surface of bend.

4.1.6 Spectroscopy results: -

The spectrographic analysis of failed pipe bend was done and the results in the form of elemental percentage are given in Table 4.3 and the density of the material is taken as 7850Kg/m³.

Table 4.3 Elemental results of failed pipe bend

C%	Si%	Mn %	S%	P%	Cr %	Ni %	Mo %	Al %	Cu %	V%	Nb %	Ti%
0.1228	0.0140	0.360	0.0148	0.0112	0.0472	0.0337	0.0049	0.0555	0.0359	0.0019	<0.0010	<0.0010

4.2 Bend erosion experimental setup results

Experiments are performed on the setup and due to recirculation of sand particles the mean effective particle size of sand particle is calculated by sieve analysis. 20 Kg Sand was used to recirculate through the test rig and for 100 kg circulation 5 run required. The silica sand quality degraded hence to find results of mean effective particle size of fresh silica sand, after 5 run and 10 run respectively. 200 gram of sample is used to perform sieve analysis. Sieves of sizes from 63, 90, 106, 125, 150, 180, 212 and 250 μ m are used to find cumulative weight of oversized particles in each sieve shown in table 4.4 and after that percentage oversize was calculated. This data was plotted in Fig. 4.9 and it was found that 50 % cumulative weight was found for 200 μ m of fresh silica sand.

Table 4.4 Fresh silica sand particle size

Sieve size in μm	Cumulative weight in grams	% oversize
>250	73	36.5
>212	118.1	59.05
>180	118.3	59.15
>150	138.7	69.35
>125	140.2	70.1
>106	171.5	85.75
>90	180.9	90.45
>63	186.2	93.1
<63	200	100

In Fig 4.9, 50 % oversized found at 200 μm , hence the mean effective particle size was considered as 200 μm for fresh silica sand.

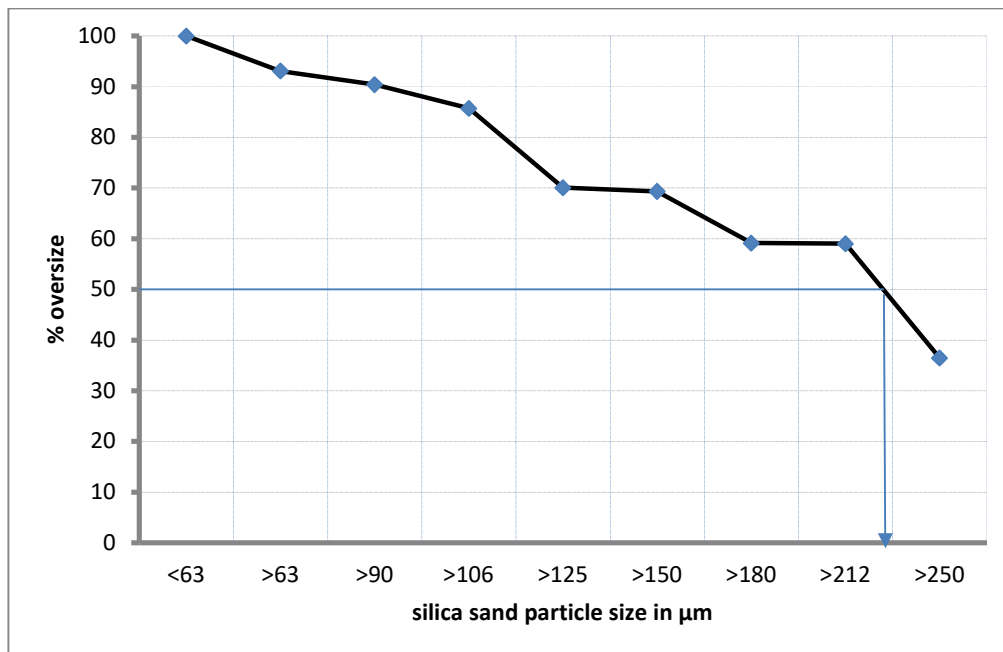


Fig. 4.9 Fresh silica sand without swirling

Sieve analysis of silica sand after 5 runs found that 50 % oversized at 150 μ m, hence the mean effective particle size was considered as 150 μ m for silica sand after 5 run as per Fig. 4.10 and. Table 4.5 shows the results of sieve analysis of % oversized.

Table 4.5 silica sand particle size after 5 run

Sieve size in μ m	Cumulative weight in grams	% oversize
>250	37.5	18.75
>212	83.4	42.7
>180	83.7	42.85
>150	108.2	54.1
>125	109.99	54.995
>106	152.4	76.2
>90	164.6	82.3
>63	173	86.5
<63	200	100

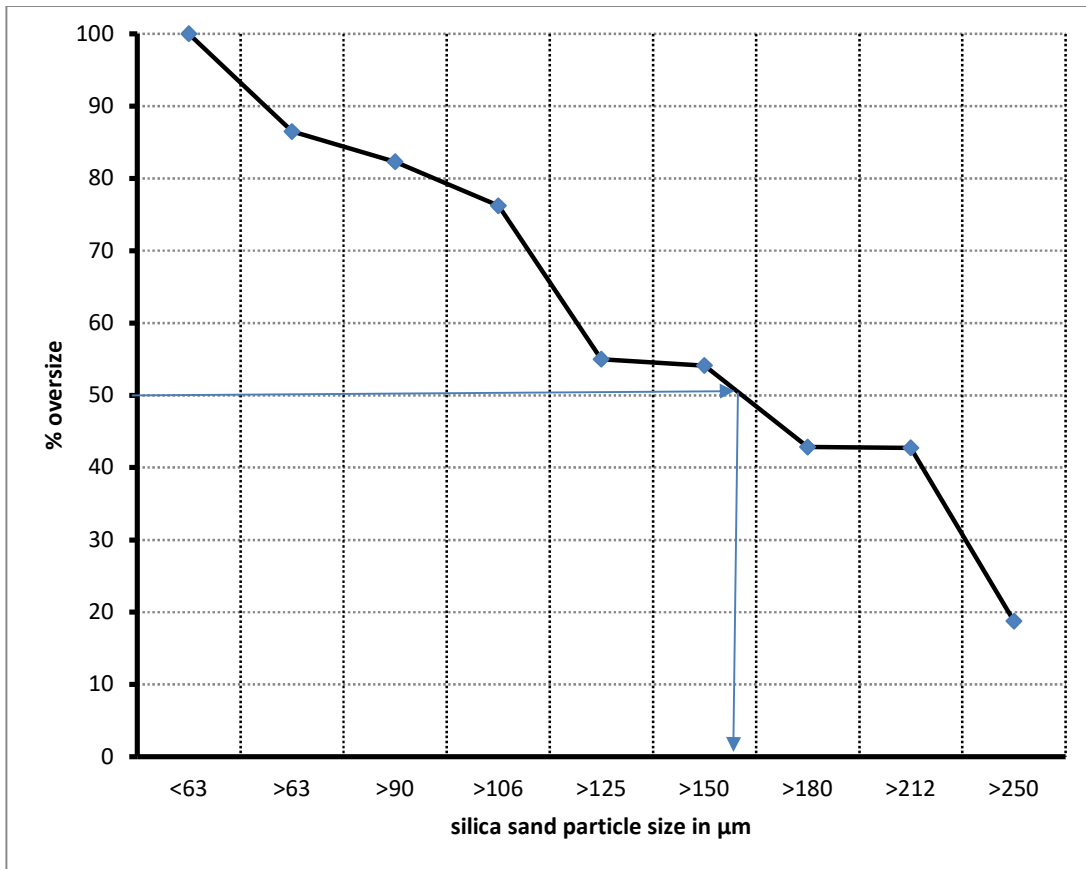


Fig. 4.10 silica sand particle size without swirling device after 5 run

Sieve analysis of silica sand after 10 runs found that 50 % oversized at 125 μ m, hence the mean effective particle size was considered as 125 μ m for silica sand after 10 run as shown in Fig. 4.11 and sieve analysis % oversized results are tabulated in Table 4.6.

Table 4.6 silica sand particle sizes without swirling device after 10 run

Sieve size in μ m	Cumulative weight in grams	% oversize
>250	17.3	8.65
>212	64.5	32.25
>180	65	34.5
>150	96	48
>125	100.9	50.45
>106	146.3	73.15
>90	161.7	85.85
>63	172.2	86.1
<63	200	100

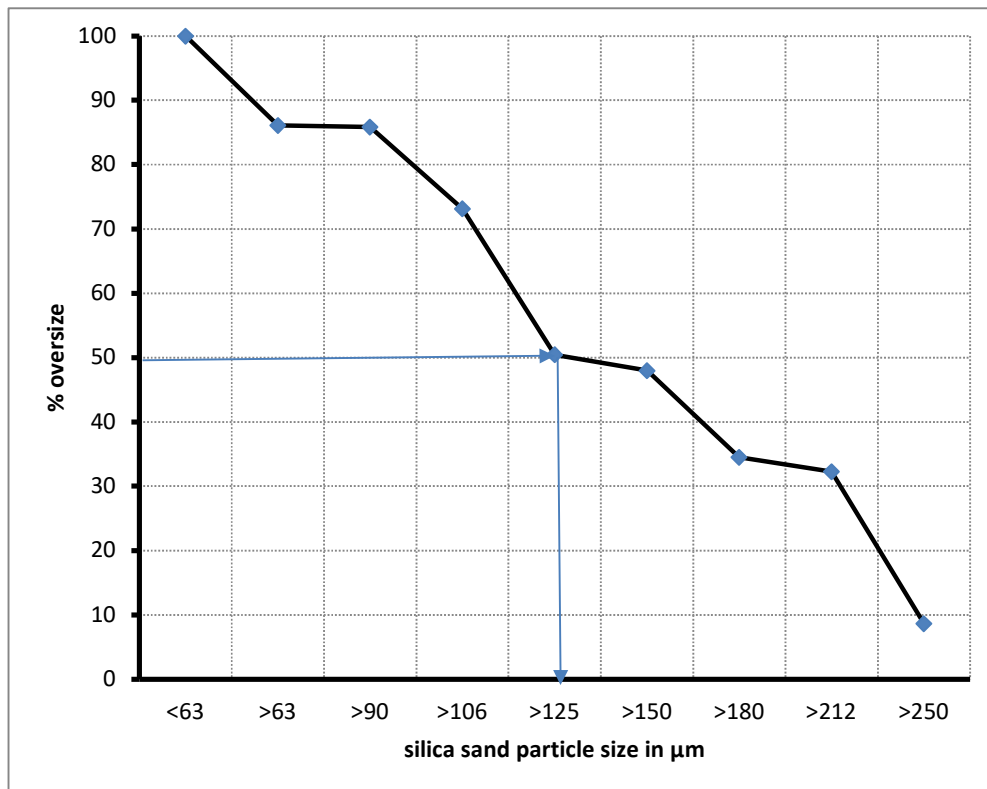


Fig. 4.11 silica sand particle sizes without swirling device after 10 run

4.2.1 Operating parameters for experimentation:

Operating parameters for Experiments of without swirling device and with motor operated swirling device and with auto swirling device were tabulated in table 4.7 shown:

Table 4.7 Operational parameters for swirling experiments

Operational parameters for swirling experiments	
Parameters	Value
Rotary feeder speed	125 rpm
Pressure of root blower	1 bar
Free air CFM	100 cfm= 0.0472m ³ /sec
Cycle time (sec.)	40*60=2400 Sec
Mass flow rate (Particle)	0.074 kg/sec
Mass flow rate (Air)	0.0547 kg/Sec
inlet velocity (Air)	23.11m/sec
Swirling device speed	35 rpm
Distance of swirling device from bend	0.5 m
Horizontal Length	1000mm
Vertical Length	500 mm
Swirling device length	500 mm
Diameter of Pipe	51mm
Angle	90°
Air Density	1.293 kg/m ³
Silica Sand Density	2000 kg/m ³
Viscosity	1.8×10 ⁻⁵ kg. m-1.s -1
Particle size	200,250,300 µm
Solid Loading Ratio (SLR)	2
Erosion Photograph and weight loss in bends due to bend erosion are considered as performance parameters.	

4.2.2 Experiments Results:

Experimental Results photographs of without swirling and motor operated swirling device were shown in Fig. 4.12. Erosion patterns are clearly shown on the photograph without swirling while very less erosion pattern was shown with swirling prove the effectiveness of swirling device.

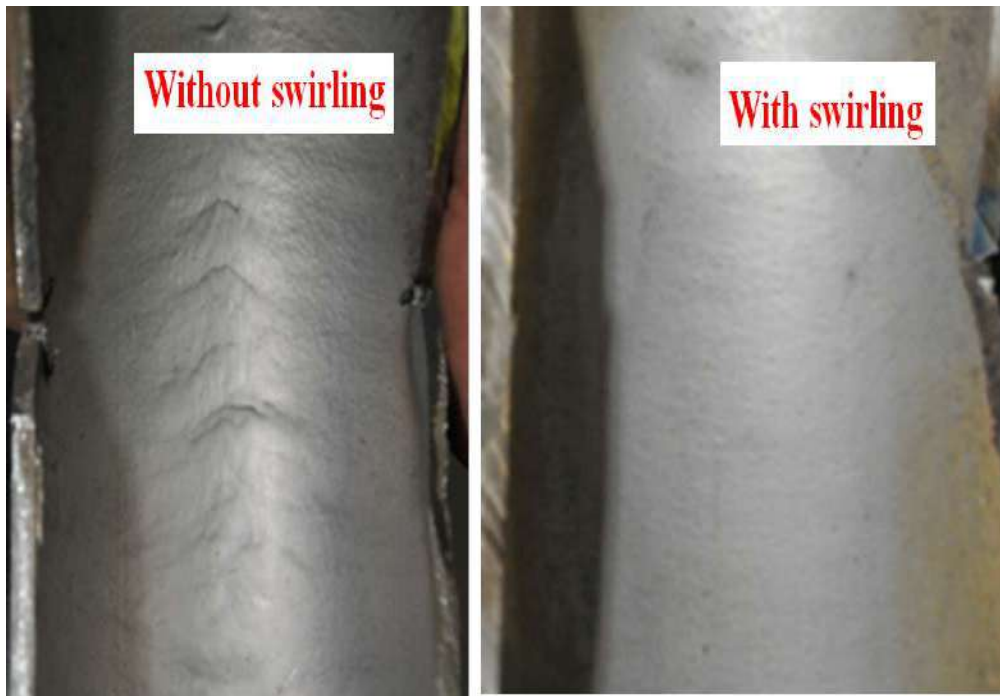


Fig. 4.12 Effect of swirling on bend

In Table 4.8, Experimental results without a swirling device, with a motor-operated swirling device at 35 rpm, and an auto swirling device are shown. These results show that the motor-operated swirling device was found to be more effective than the auto swirling device.

Table 4.8 Experimental result

Particle Size μm	Bend erosion without Swirling Device (In gms)	Bend Erosion with motor operated swirling at 35 rpm (In gms.)	Bend Erosion with auto swirling (In gms.)
200	4	2	3
150	3.3	1.4	2.6
125	2.7	0.9	2.1

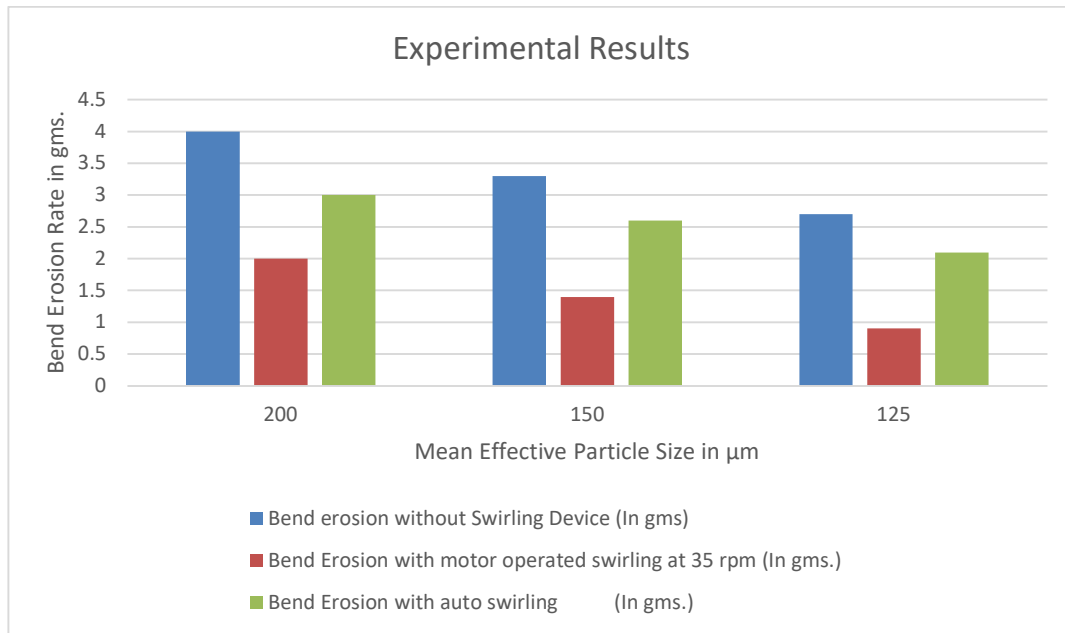


Fig. 4.13 Experimental Data Graph

In Fig. 4.13 results are plotted in a histogram which shows that as particle size decrease bend erosion rate decreases and motor operated swirling device produces best results. Experimental results of without swirling, motor operated swirling device and auto swirling device are tabulated in table and graphs show the effectiveness of swirling device. As mep decreases erosion rate decreases and motor operated swirling device was found more effective.

4.3 CFD Results

CFD Results are categorized into four cases discussed below: -

- i. Bend Erosion without Swirling Device
- ii. Bend Erosion Rate with a 90° bend with Motor-operated Swirling Device
- iii. Bend Erosion Rate at different bend angles with Motor-operated Swirling Device
- iv. Bend Erosion Rate with auto swirling Device.

4.3.1 CFD Numerical Prediction Swirling Device Motor Operated: -

In bend it is observed that mechanism of bombardment of particles on inner side of bend punctured it due to bend erosion. So, to change the mechanism of bombardment a swirling device Motor operated is used to rotate a part of pipe. The CFD modelling is carried out for 90° Bend with and without swirling device using k-omega ($k-\omega$) model validated with

literature data [44] as shown in Fig. 4.14 and 4.15 are used and results analyzed. Model dimensions is shown in Table 4.9.

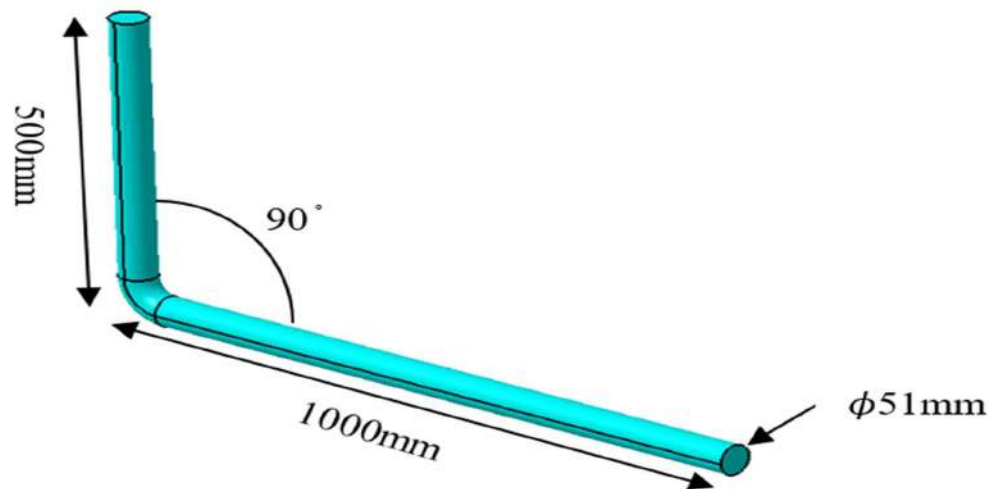


Fig. 4.14 Bend without Motor Operated Swirler

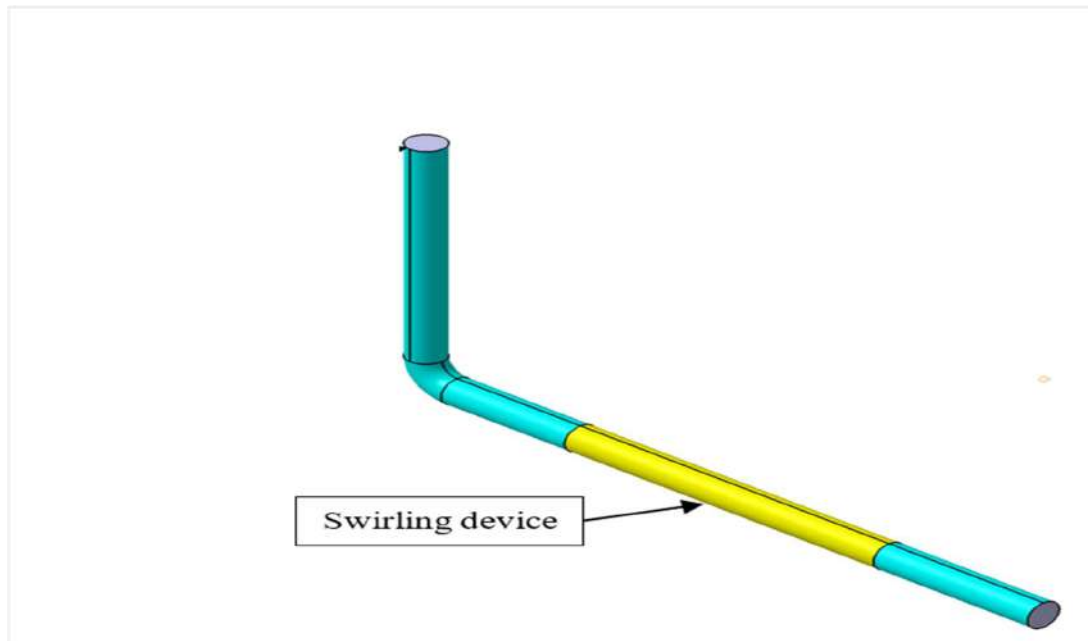


Fig. 4.15 Bend with Motor operated swirler

Table 4.9 Operating Parameters for CFD modelling

Boundary condition		
Rotary feeder speed (RPM)	125	
Pressure of root blower (Bar)	1	
Free air CFM (m ³ /sec)	100CFM=0.0472	
Cycle time (sec.)	45*60=2700	
Mass flow rate (Particle) (kg/Sec)	0.074	
Mass flow rate (Air) (kg/Sec)	0.0547	
inlet velocity (Air) (m/sec)	23.11	
Swirling device speed (rpm)	35,70,100	
Distance of swirling device from bend (m)	0.5	
Nodes and elements	30548 and157241(grid independence test)	
Solid Loading Ration (SLR)	2	
Model Dimensions		
Horizontal Length (mm)	1000	
Vertical Length (mm)	500	
Swirling device length (mm)	500	
Diameter of Pipe (mm)	51	
Angle (°)	90	
CFD Material Properties		
	Silica	Air
Density (kg/m ³)	2000	1.293
Viscosity (kg. m-1.s -1)	-	1.8×10-5
Particle size (µm)	200,250,300	-

4.3.2 Validation of CFD

CFD model was validated through Experimental data. Experimental Data of erosion of pipe bend was validated with 15 % error Shown in Fig. 4.16.

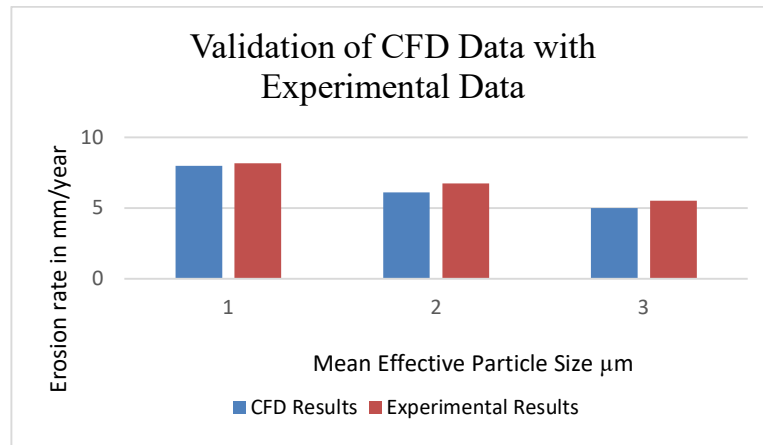


Fig. 4.16 Model Validation

4.3.3 Grid Independence Test:

To find the correct meshing for CFD analysis grid independence test was performed shown in Fig. 4.17 and nodes and elements found are 30548 and 157241. Meshing Details are shown in Fig. 4.18.

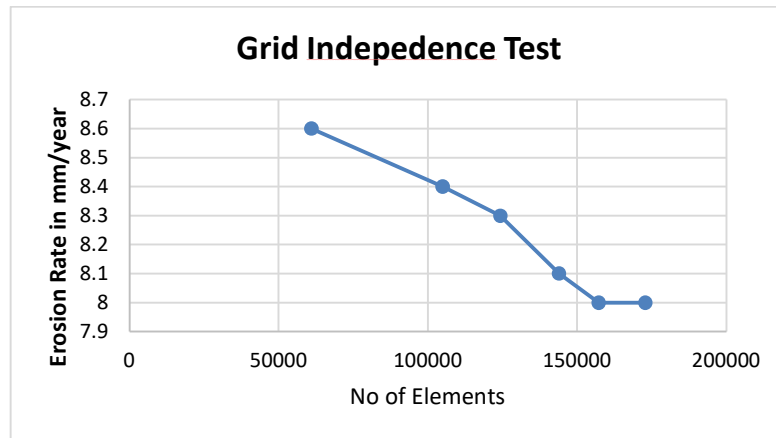


Fig. 4.17 Grid Independence Test

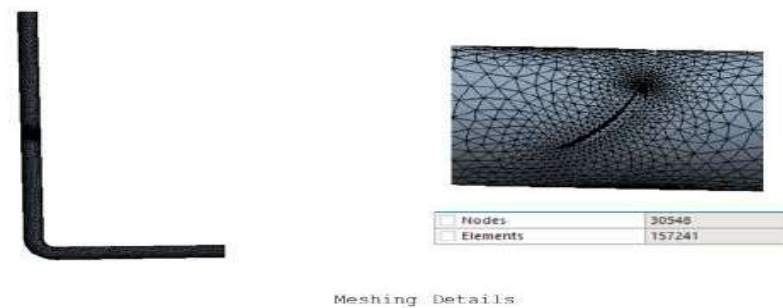


Fig. 4.18 Meshing Details of CFD model

4.3.4 CFD Results for 90° bend

In results erosion rate is calculated in mm/year or in $\text{kg/m}^2\text{s}$

So the expression for the conversion is shown in equation 4.4

$$\text{Erosion in mm/year} = \text{Erosion Rate Density}(\text{kg/m}^2\text{s}) / 7850 [\text{kg m}^{-3}] * 1000 [\text{mm}] / 1 [\text{m}] * 3600 * 8760 \quad 4.4$$

In case-1 particle size was $200\mu\text{m}$ without swirling. The velocity in this case increases up to 13.3m/s . pipe total erosion rate is 8.0mm/year . The CFD results contours are shown in Fig. 4.19. the maximum erosion rate was recorded as $9.01 \times 10^{-6} \text{kg/m}^2\text{s}$ and velocity $1.343 \times 10^2 \text{m/s}$.

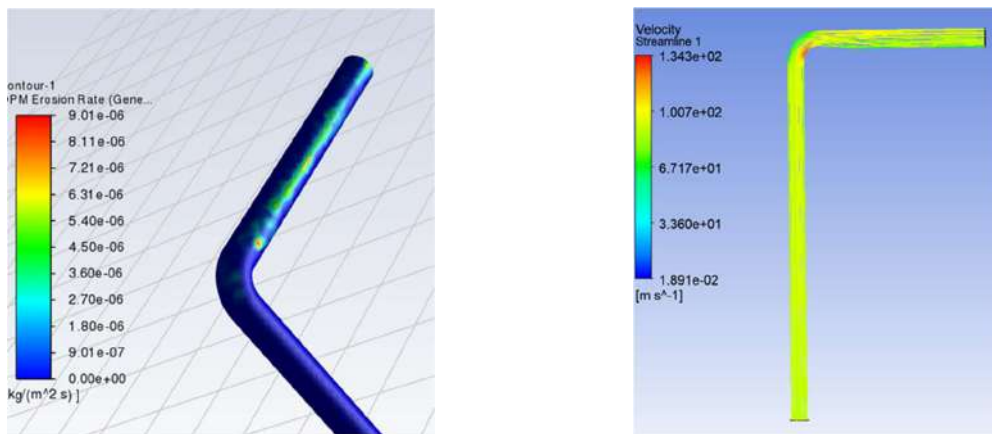


Fig. 4.19 Erosion rate and velocity contour at $200 \mu\text{m}$ particle size without swirling device

Case-2 Particle size $250 \mu\text{m}$ and without swirling device.

In case-2 particle size was $250\mu\text{m}$. The velocity in this case increases up to 37.5m/s . pipe total erosion rate is 10.0mm/year . The CFD results contours are shown in Fig. 4.20.

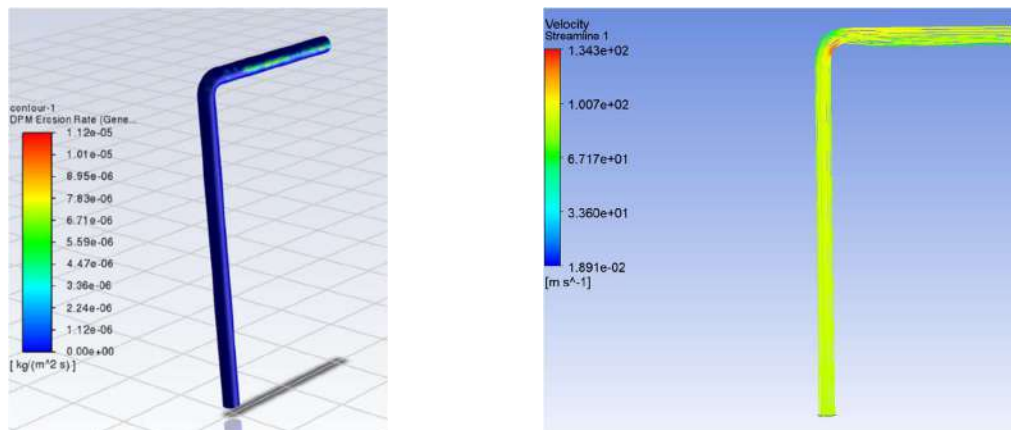


Fig. 4.20 Erosion rate and velocity contour at $250 \mu\text{m}$ particle size without swirling device

Case-3 Particle size 300 and without swirling device.

In case-3 particle size was 300 μm . The velocity in this case increases up to 53.0m/s. pipe total erosion rate is 12.0mm/year. The CFD results contours are shown in Fig.4.21 Without swirling bend erosion rate is detrimental to pcs and creates very fast puncture of bend

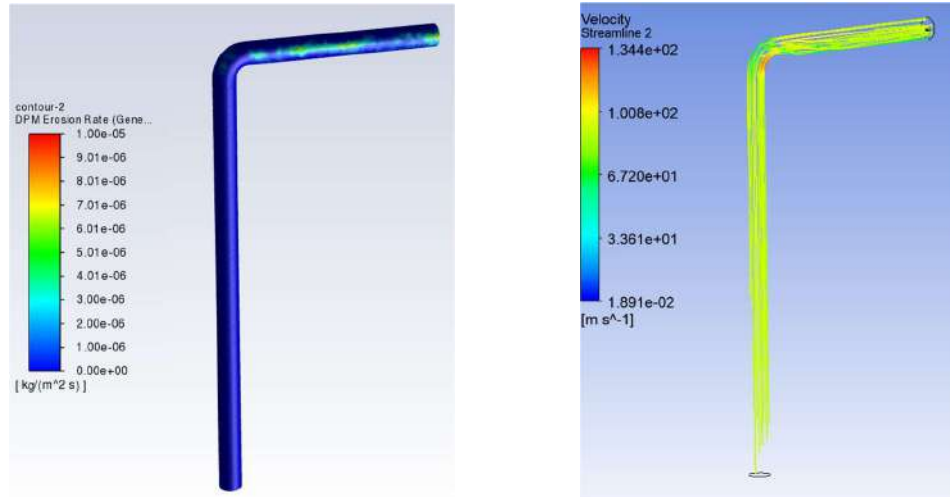


Fig. 4.21 Erosion rate and velocity contour at 250 μm particle size without swirling device

Case-4 Particle size 200 with a swirling device. 35rpm

In case-4 particle size was 200 μm . The velocity in this case increases up to 40.6m/s. pipe total erosion rate is 6.42mm/year. The CFD results contours are shown in Fig.4.22.

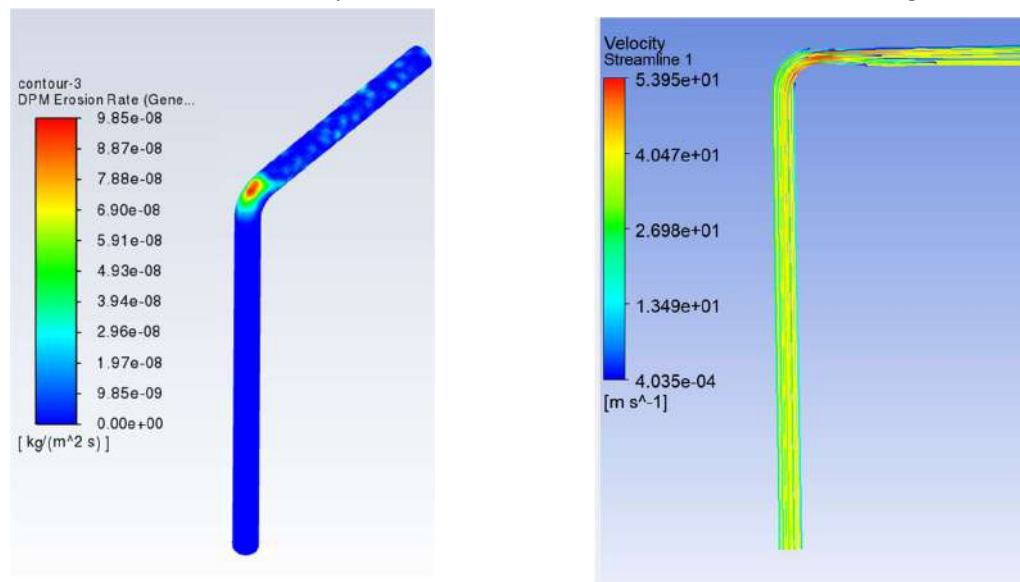


Fig. 4.22. Erosion rate and velocity contour at 220 μm particle size with swirling device(35rpm)

Case-5 Particle size 250 and with swirling device. 35rpm

In case-5 particle size was 250 μm . The velocity in this case increases up to 48.3m/s. pipe total erosion rate is 8.03mm/year. The CFD results contours are shown in Fig. 4.23.

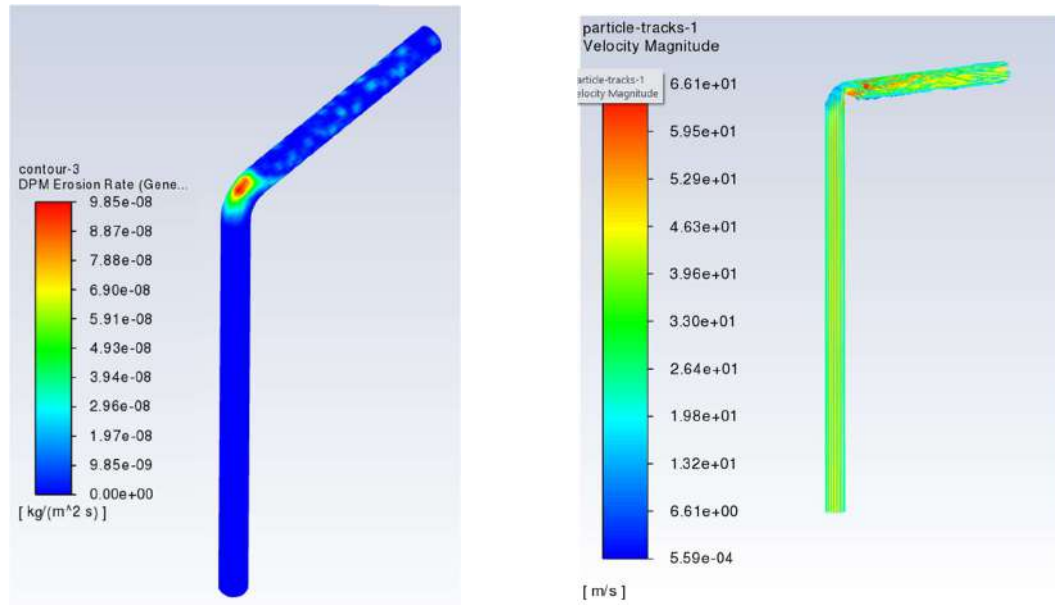


Fig. 4.23 Erosion rate and velocity contour at 250 μm particle size with swirling device(35rpm)

Case-6 Particle size 300 and with swirling device. 35rpm

In case-6 particle size was 300 μm . The velocity in this case increases up to 68.9m/s. pipe total erosion rate is 9.63mm/year. The CFD results contours are shown in Fig. 4.24.

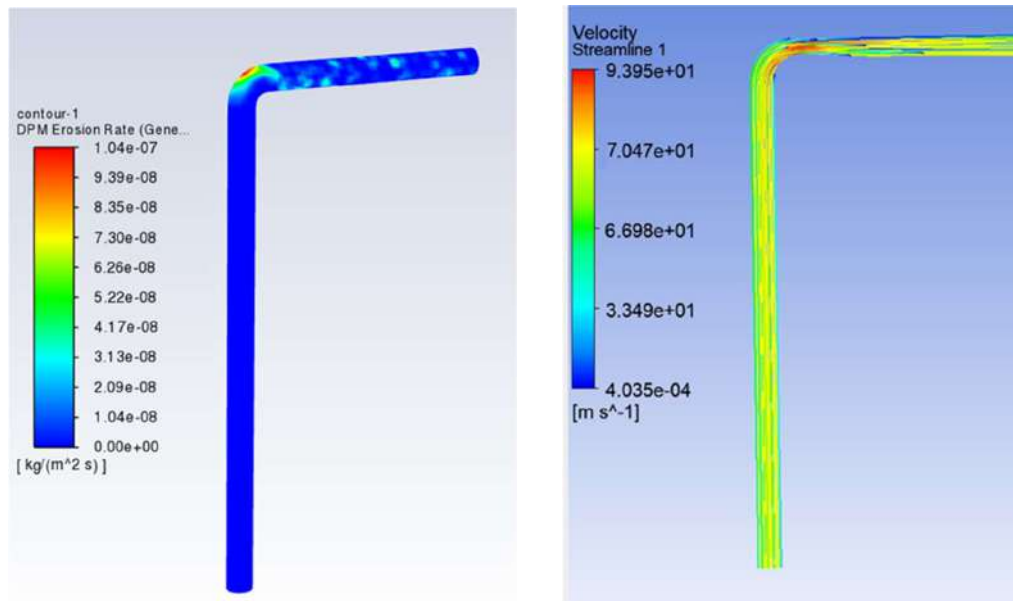


Fig. 4.24 Erosion rate and velocity contour at 300 μm particle size with swirling device(35rpm)

Case-7 Particle size 200 and with swirling device. 70rpm

In case-7 particle size was 200 μm . The velocity in this case increases up to 52.8m/s. pipe total erosion rate is 5.14mm/year. The CFD results contours are shown in Fig.4.25.

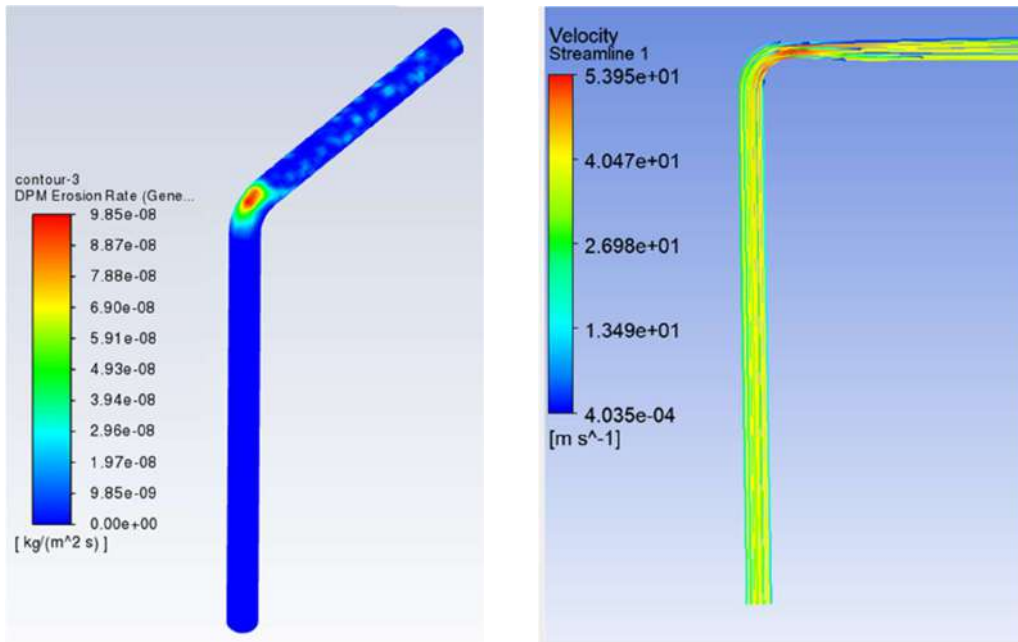


Fig. 4.25 Erosion rate and velocity contour at 200 μm mep with swirling device (70rpm)

Case-8 Particle size 250 and with swirling device. 70rpm

In case-8 particle size was 250 μm . The velocity in this case increases up to 63.4m/s. pipe total erosion rate is 6.42mm/year. The CFD results contours are shown in Fig. 4.26.

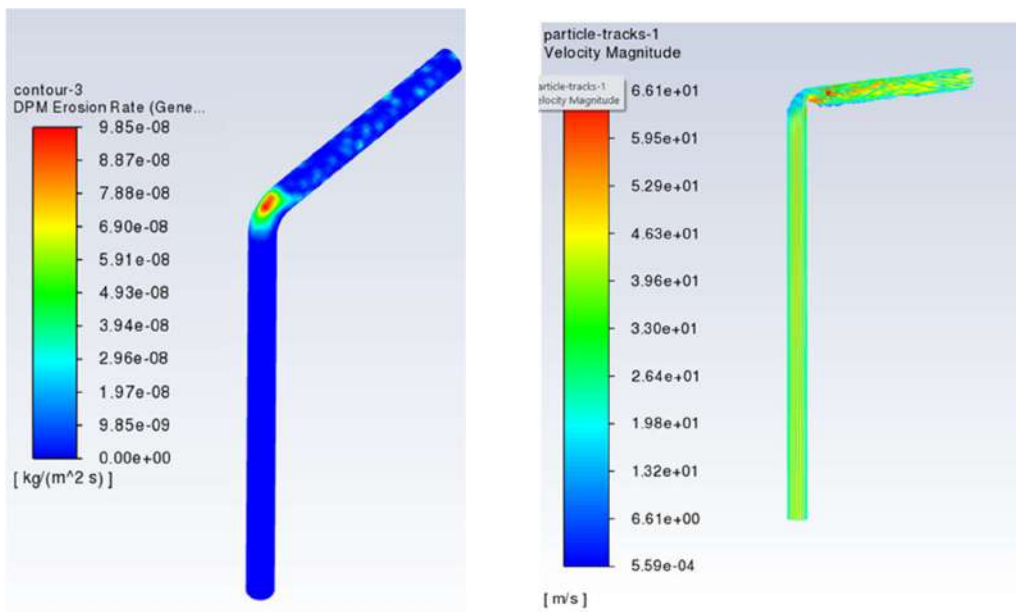


Fig. 4.26 Erosion rate and velocity contour at 250 μm mep with swirling device(70rpm)

Case-9 Particle size 300 and with swirling device. 70rpm

In case-9 particle size was 300 μm . The velocity in this case increases up to 89.6m/s. pipe total erosion rate is 7.70mm/year. The CFD results contours are shown in Fig. 4.27

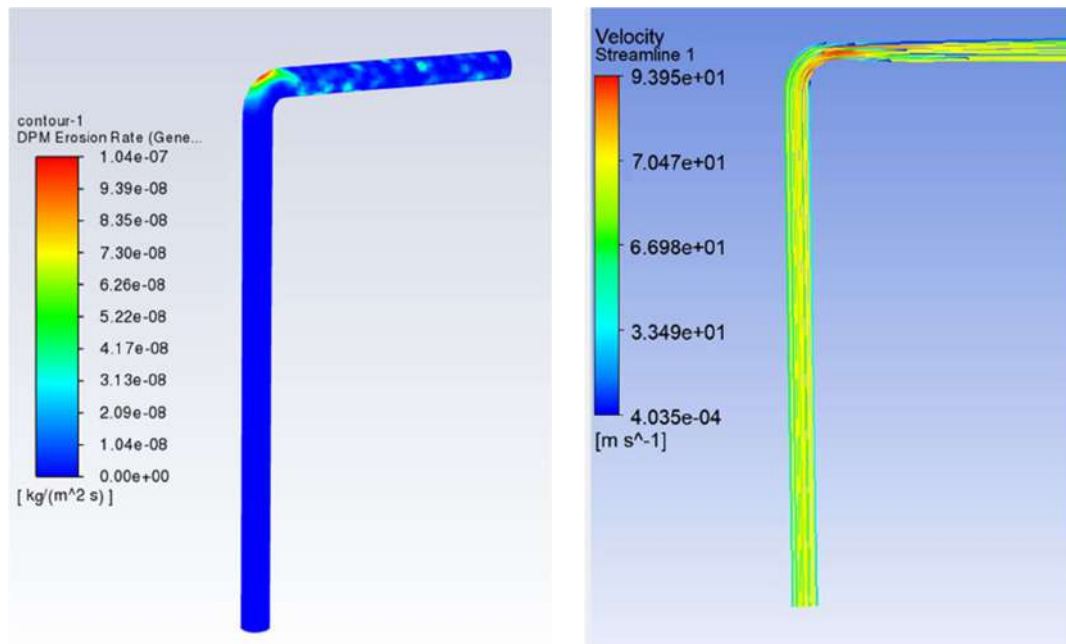


Fig. 4.27 Erosion rate and velocity contour at 300 μm mep with swirling device(70rpm)

Case-10 Particle size 200 and with swirling device. 100rpm

In case-10 particle size was 200 μm . The velocity in this case increases up to 68.7m/s. pipe total erosion rate is 4.0mm/year. The CFD results contours are shown in Fig. 4.28.

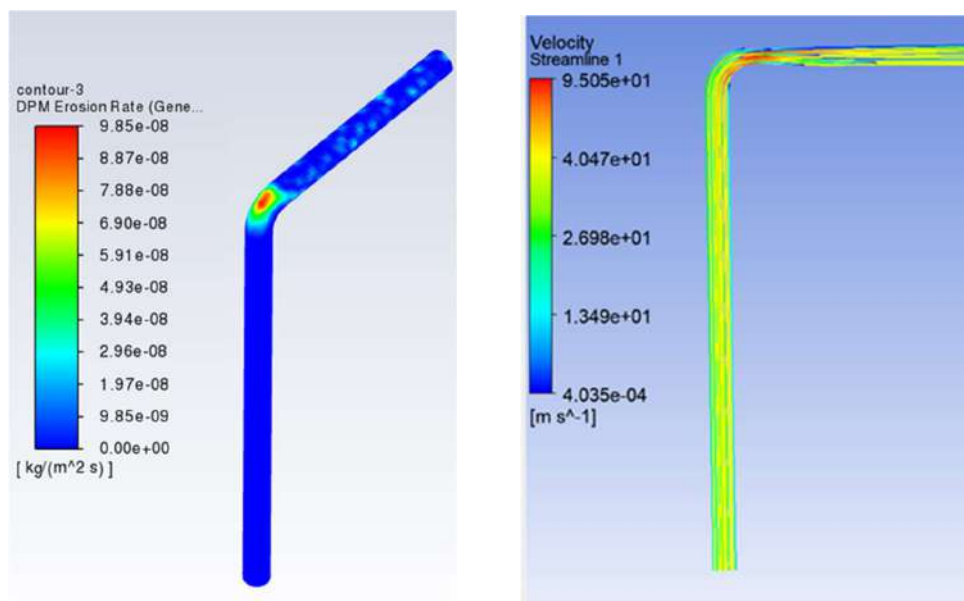


Fig. 4.28 Erosion rate and velocity contour at mep 200 μm with swirling device(100rpm)

Case-11 Particle size 250 and with swirling device. 100rpm

In case-11 particle size was 2500 μm . The velocity in this case increases up to 82.4m/s. pipe total erosion rate is 5.0mm/year. The CFD results contours are shown in Fig. 4.29.

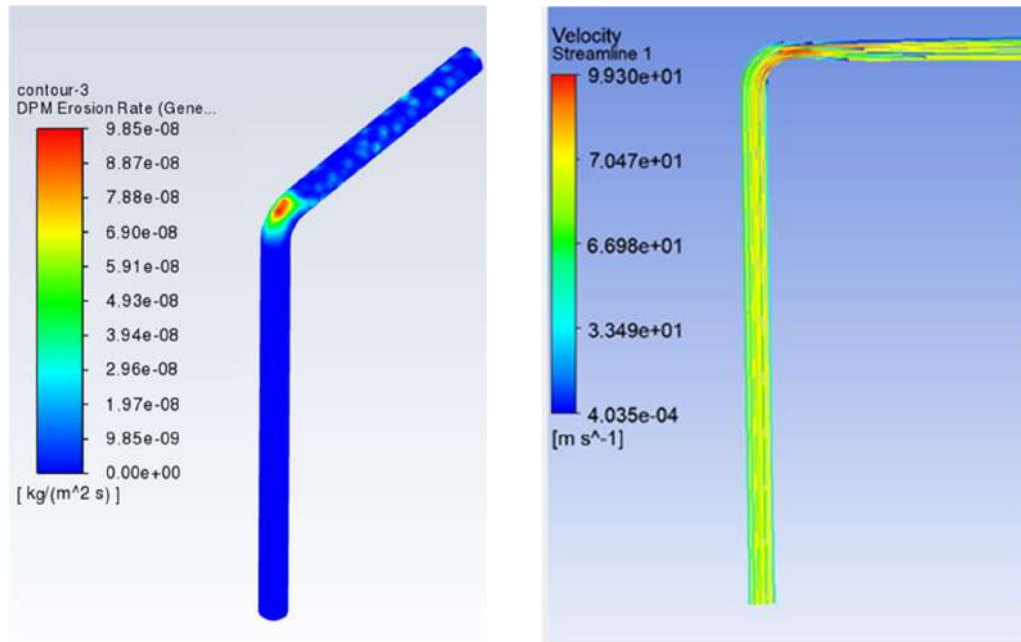


Fig. 4.29 Erosion and velocity contour at mep 250 μm with swirling device(100rpm)

Case-12 Particle size 300 and with swirling device. 100rpm

In case-12 particle size was 300 μm . The velocity in this case increases up to 116.4m/s. pipe total erosion rate is 5.0mm/year. The CFD results contours are shown in Fig. 4.30.

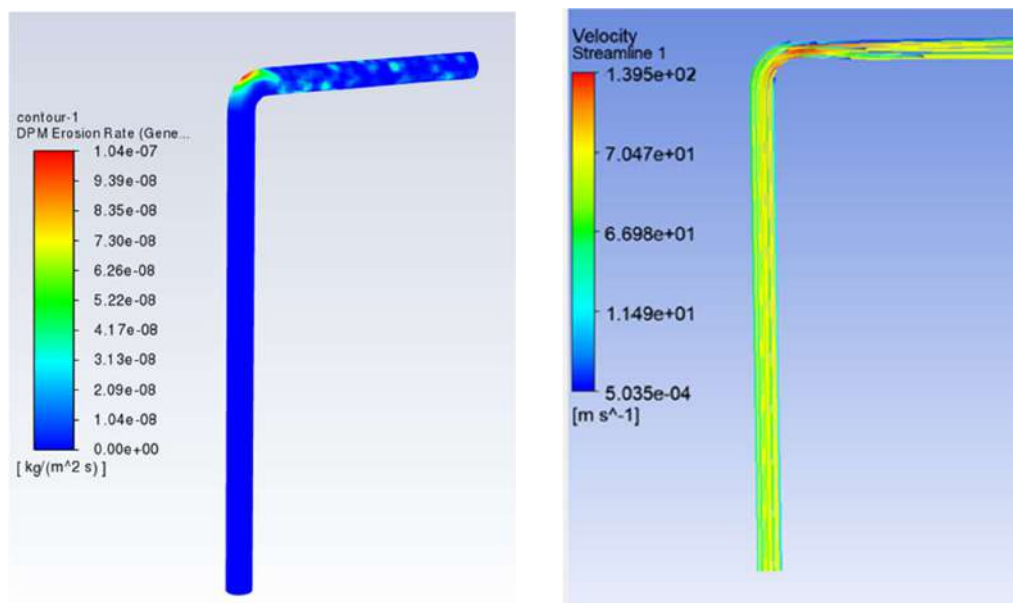


Fig. 4.30 Erosion and velocity contour at mep 300 μm particle size with swirling device(100rpm)

As per Computational fluid dynamic results the maximum erosion rates in mm/year for pipe bends with density for mild steel ' ρ ' = 7850 Kg/m³ are shown in Table 4.10. that there is maximum erosion rate reduction at 100 rpm but in practical when rpm of swirler increases then choking of material takes place due pressure drop.

Table 4.10 CFD Results

Particle size	Parameters	Unit	Bend (without swirling device)	Bend-1 (Swirling device with 35rpm)	Bend-2 (Swirling device with 70 rpm)	Bend-3 (Swirling device with 100 rpm)
200	Erosion rate	mm/year	8.0	6.42	5.14	4.0
		wt loss (g)	3.9	3.1	2.51	1.95
		% Reduction	--	20.51%	35.6%	50%
	Velocity	m/s	31.3	40.6	52.8	68.7
250	Erosion rate	mm/year	10.0	8.03	6.42	5.0
		wt loss (g)	4.88	3.92	3.1	2.44
		% Reduction	-	19.6%	36.47%	50%
	Velocity	m/s	37.5	48.8	63.4	82.4
300	Erosion rate	mm/year	12.0	9.63	7.70	6.0
		wt loss (g)	5.86	4.70	3.7	2.93
		% Reduction	-	19.7%	36.8%	50%
	Velocity	m/s	53.0	68.9	89.6	116.4

In Fig. 4.31 it demonstrates that as mean effective particle size decreases the erosion rate decreases and as rpm of swirler increases from 35rpm to 100 rpm the erosion rate reduction reaches to 50%. Hence linear indirectly proportional relationship established between erosion rate and rpm of swirler and linear directly proportional relationship established

between erosion rate and mean effective particle size as erosion rate decreases with decrement of mean effective particle size.

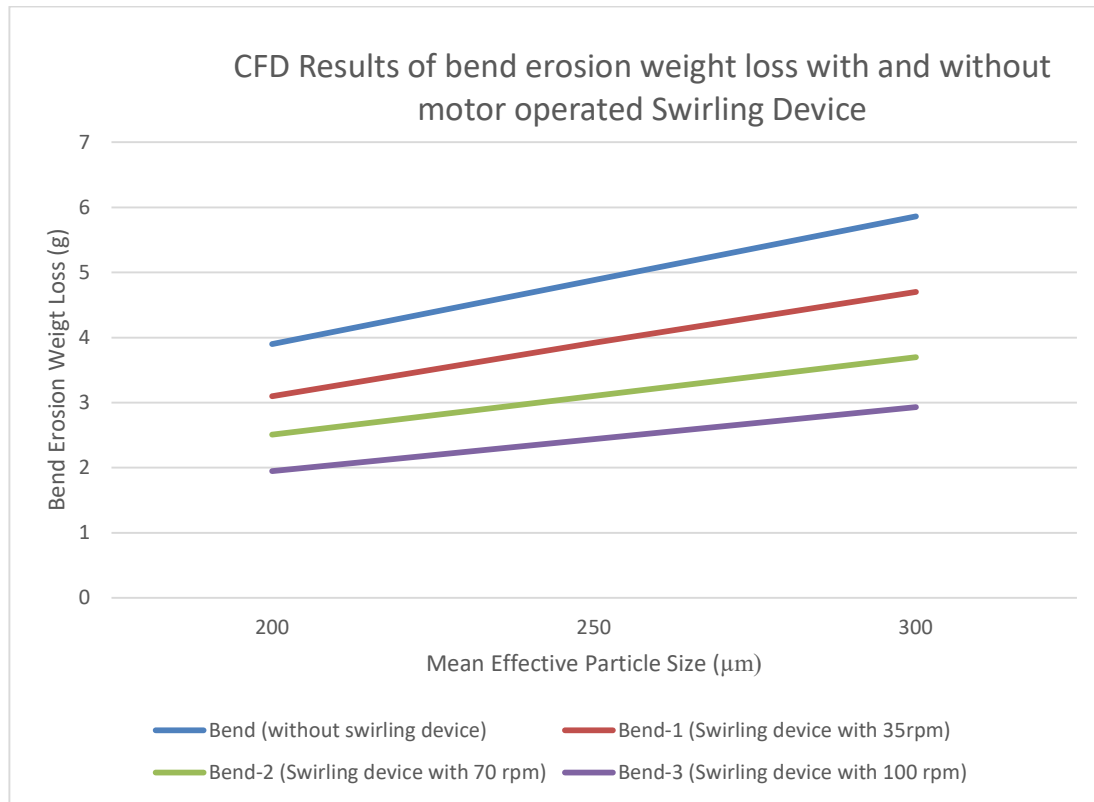


Fig. 4.31 Erosion graph at different bend conditions

4.3.5 Motor operated Swirling Device Used at different Bend Angles: -

Motor Operated Swirling Device numerical prediction at bend angles at 15°, 45°, 60° and 90° were carried out. Bend with different bend angles are shown in Fig. 4.32.

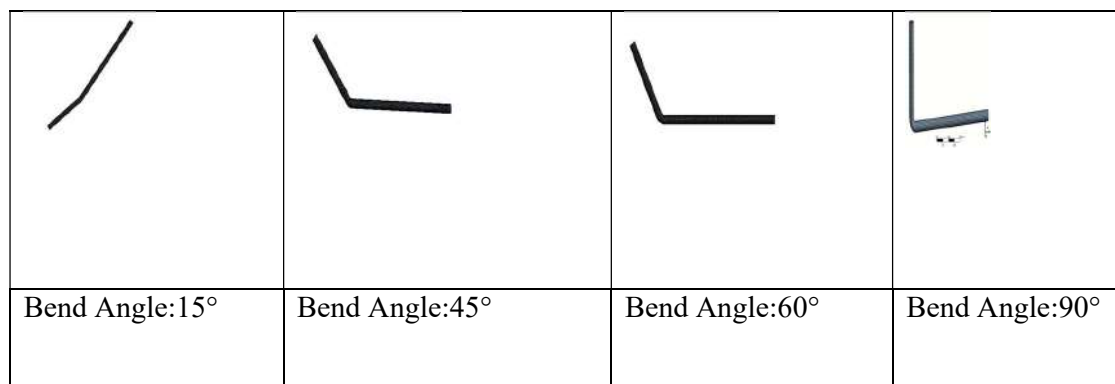


Fig. 4.32 Different bend angles

Case-1 Particle size 200 and without swirling device at angle 15°.

In case-1 particle size was 200μm. The velocity in this case is 13 m/s. pipe total erosion rate is 5.0mm/year. The CFD results contours are shown in Fig. 4.33.

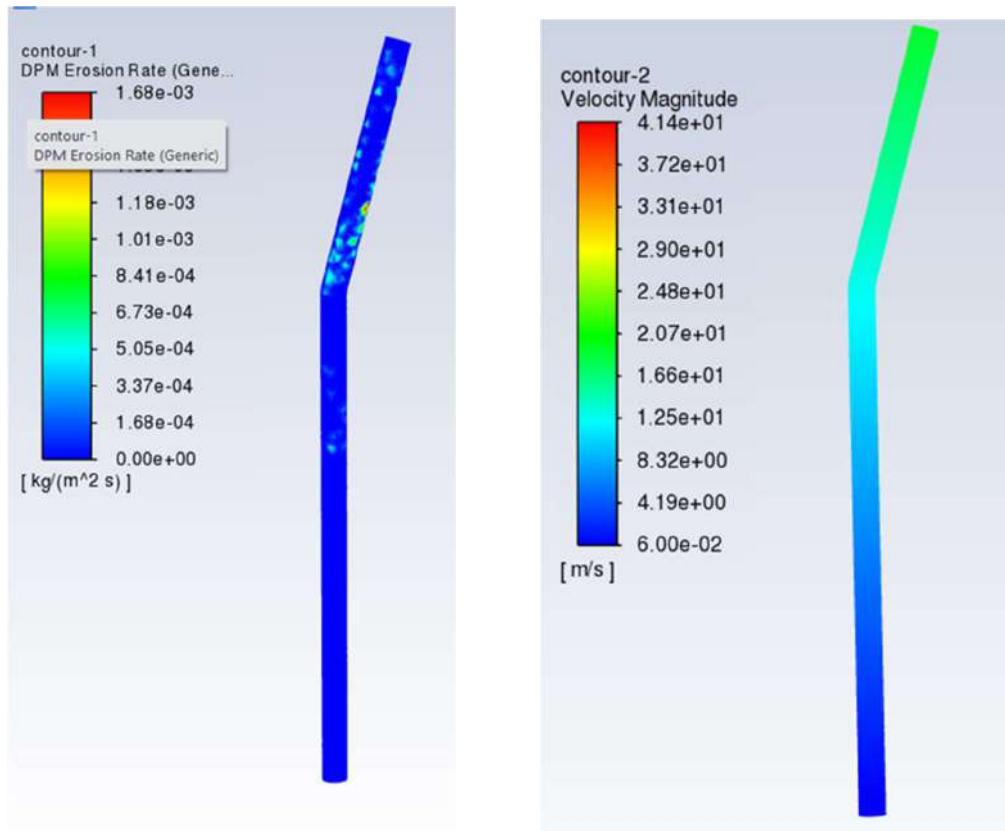


Fig. 4.33 Erosion and velocity contour at 200 μm particle size without swirling device

Case-2 Particle size 200 and without swirling device at angle 45°

In case-2 particle size was 200 μm . The velocity in this case is 15 m/s. pipe total erosion rate is 3.3mm/year. The CFD results contours are shown in Fig. 4.34.

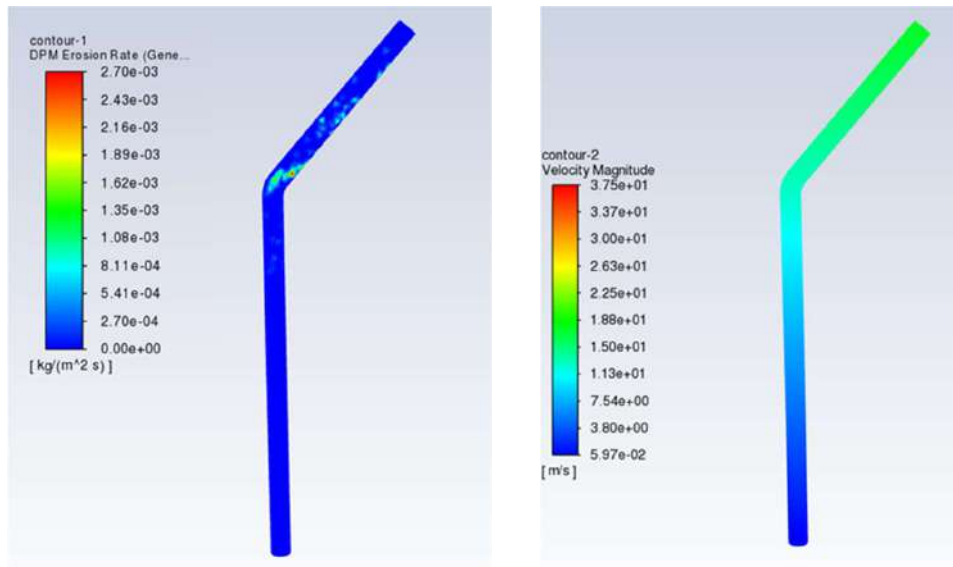


Fig. 4.34 Erosion and velocity contour at 200 μm particle size without swirling device

Case-3 Particle size 200 and without swirling device at angle 60°.

In case-3 particle size was 200 μ m. The velocity in this case 18 m/s. pipe total erosion rate is 7.2mm/year. The CFD results contours are shown in Fig. 4.35.

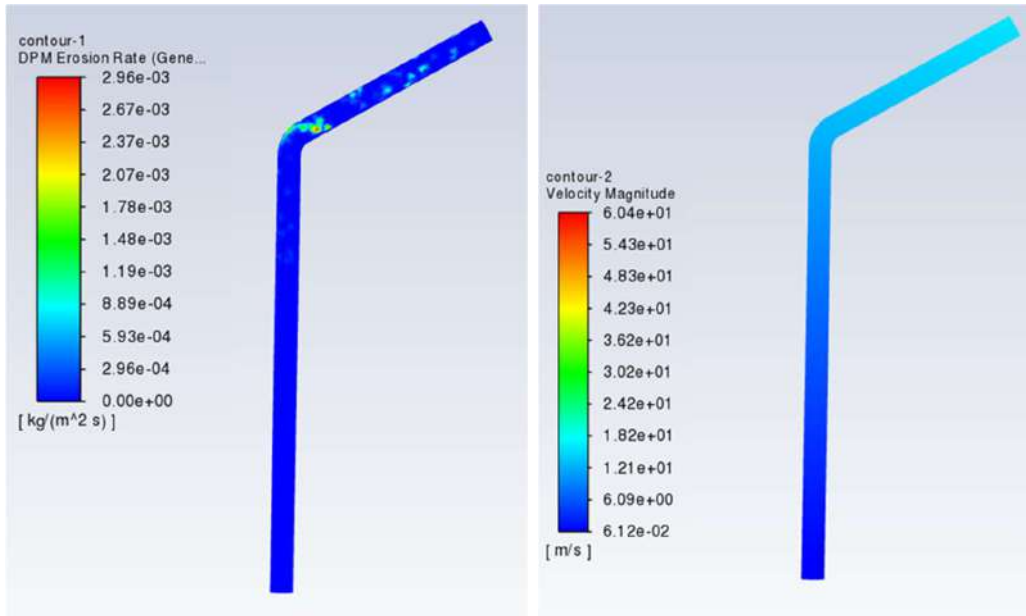


Fig. 4.35 Erosion rate and velocity contour at 200 μ m particle size with swirling device

Case-4 Particle size 200 and without swirling device at angle 90°.

In case-4 particle size was 200 μ m. The velocity in this case increases up to 31.3m/s. pipe total erosion rate is 8.0mm/year. The CFD results contours are shown in Fig. 4.36.

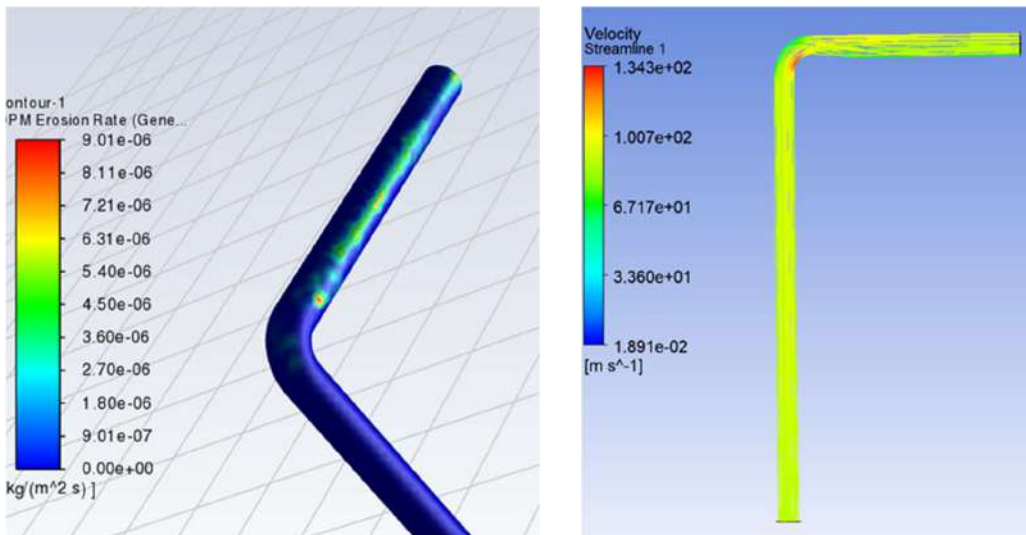


Fig. 4.36 Erosion rate and velocity contour at 200 μ m particle size without swirling device

Case-5 Particle size 200 and with swirling device. 100rpm at 15°

In case-5 particle size was 200 μ m. The velocity in this case 25 m/s. pipe total erosion rate is 2.5 mm/year. The CFD results contours are shown in Fig. 4.37

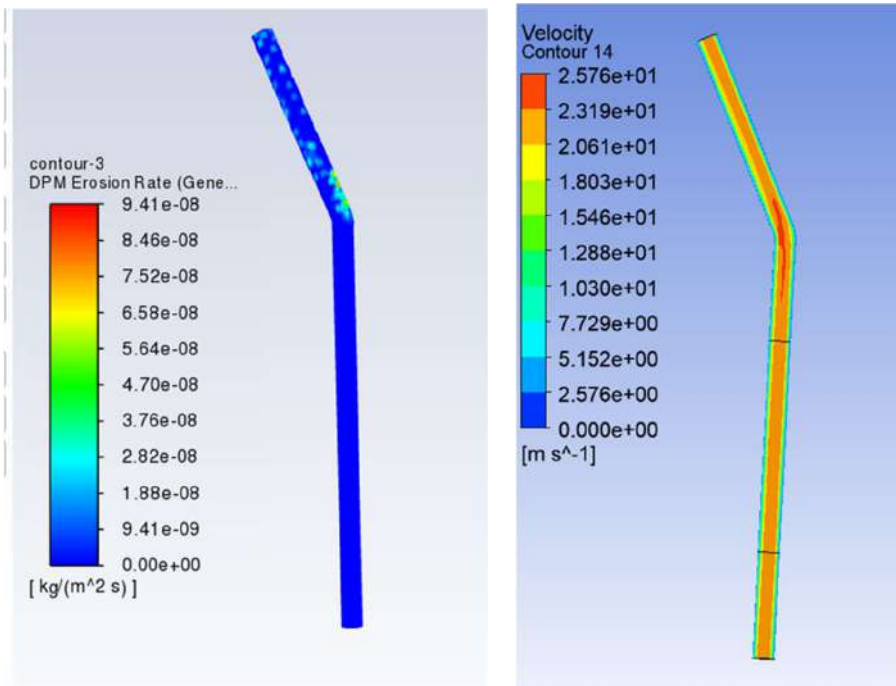


Fig. 4.37 Erosion rate and velocity contour at 200 μ m particle size with swirling device

Case-6 Particle size 200 and with swirling device. 100rpm at 45°

In case-6 particle size was 200 μ m. The velocity in this case 26 m/s. Pipe total erosion rate is 3.3mm/year. The CFD results contours are shown in Fig. 4.38.

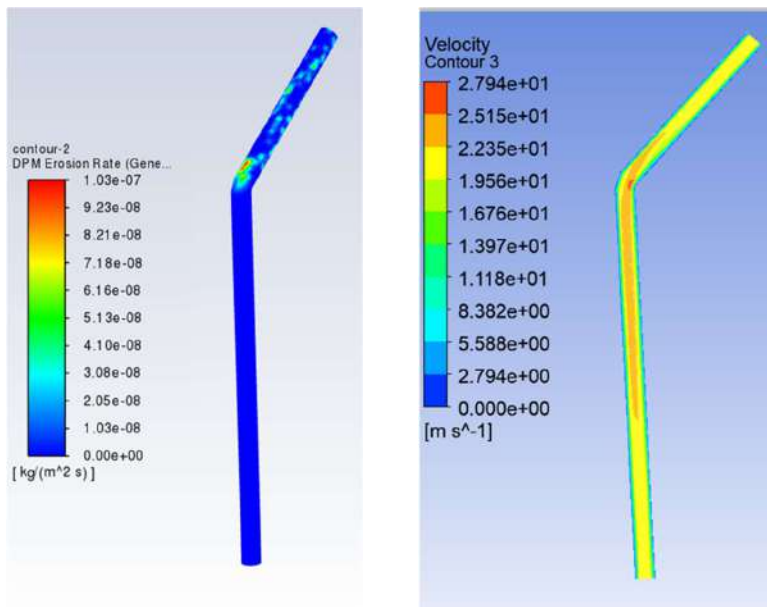


Fig. 4.38 Erosion rate and velocity contour at 200 μ m particle size with swirling device

Case-7 Particle size 200 and with swirling device. 100rpm at 60°

In case-7 particle size was 200 μ m. The velocity in this case is 26 m/s. pipe total erosion rate is 3.5mm/year. The CFD results contours are shown in Fig. 4.39.

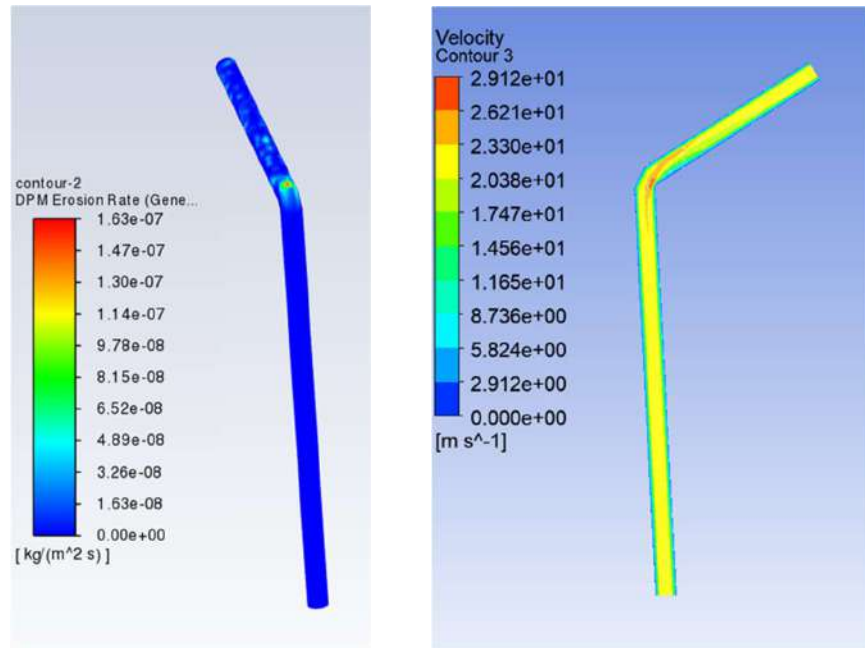


Fig. 4.39 Erosion rate and velocity contour at 200 μ m particle size with swirling device

Case-8 Particle size 200 and with swirling device. 100rpm at 90 degree

In case-8 particle size was 200 μ m. The velocity in this case 68 m/s. pipe total erosion rate is 5mm/year. The CFD results contours are shown in Fig. 4.40.

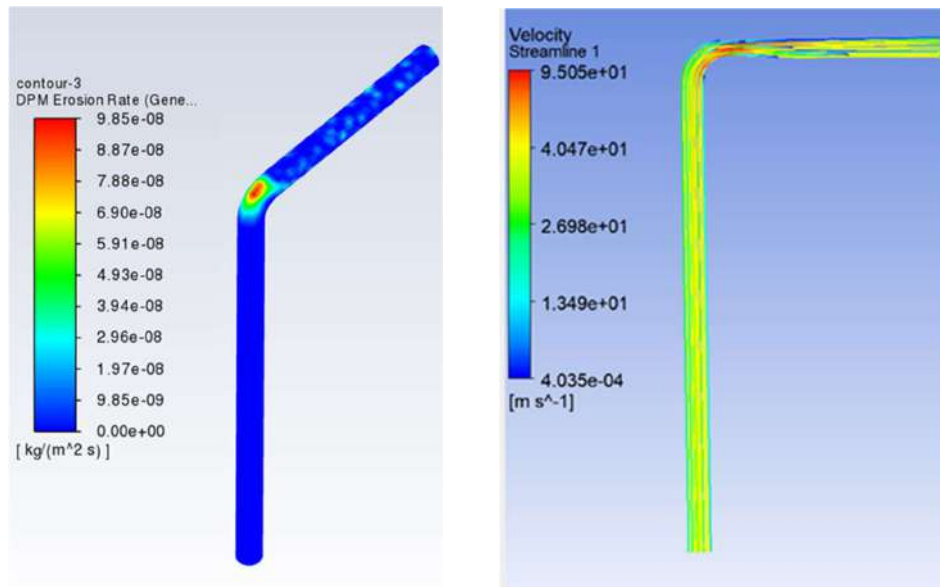


Fig. 4.40 Erosion rate and velocity contour at 200 μ m particle size with swirling device(100rpm)

As per Computational fluid dynamic result's the maximum erosion rates in mm/year for pipe bends with density $\rho = 7850 \text{ Kg/m}^3$ are shown in Table 4.11, For mean effective particle size $200\mu\text{m}$ and at 100 rpm swirling velocity nearly 50 % erosion rate reduction was reported for bend angle $15^\circ, 45^\circ, 60^\circ$ and 90° . Hence swirling devices are equally effective for all bend angles.

Table 4.11 CFD Results at different bend angles

Particle size			Unit	15°	45°	60°	90°
200 μm	Swirling device with (100 rpm)	Erosion rate	mm/year	2.5	3.3	3.5	4.0
			wt loss (g)	1.22	1.61	1.709	1.95
		Velocity	m/s	25	26	29	68.7
	without swirling device	Erosion rate	mm/year	5	6.5	7.2	8.0
			wt loss (g)	2.44	3.175	3.51	3.90
		Velocity	m/s	13	15	18	31.3
% Reduction in Bend Erosion with Swirling				50%	49.29%	51.31%	50%

In Fig. 4.41, 50% reduction in erosion rate reported with swirling device as compared to without swirling at 100 rpm of swirler and mep $200\mu\text{m}$.

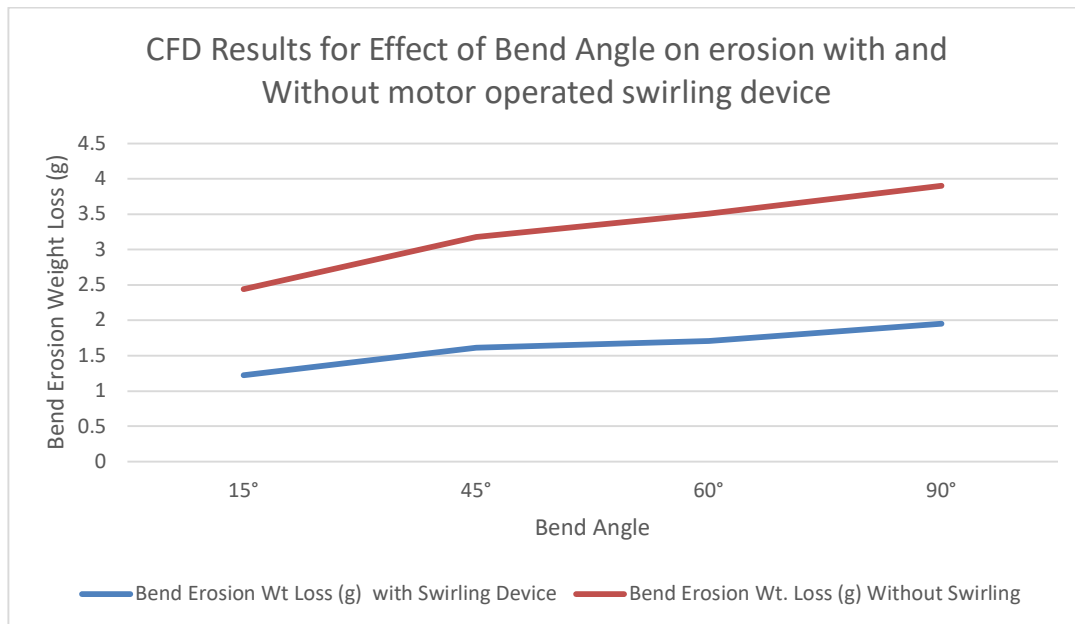


Fig. 4.41 Erosion rate graph at different bend conditions

4.3.6 CFD results of auto swirling device with blades: -

After successful results of motor operated Swirling Device, a new device with blades is made which is rotated without any external power but this device works like a turbine having one issue of erosion at blades. In Fig. 4.42 Isometric view of blades is shown. In Fig. 4.43 drawing of swirling device is demonstrated while in Fig. 4.44 swirling blade design is shown.

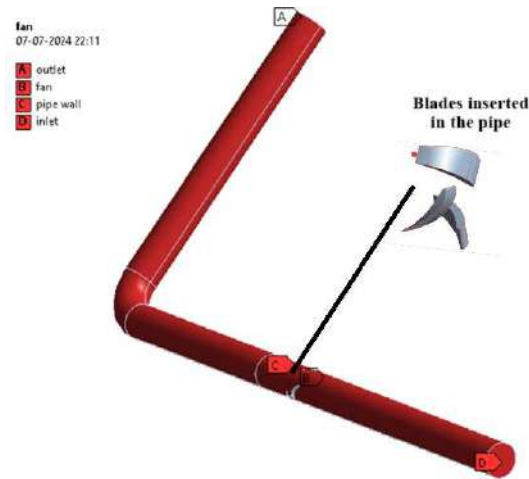


Fig. 4.42 Isometric view of CFD model with Auto swirl blades

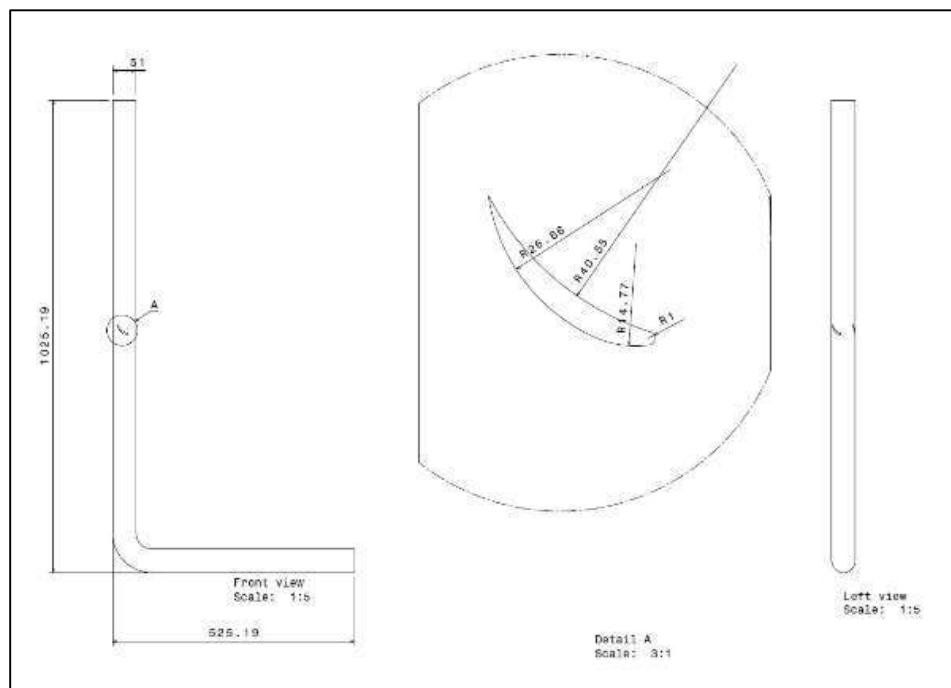


Fig. 4.43 Drawing of Auto Swirling Device

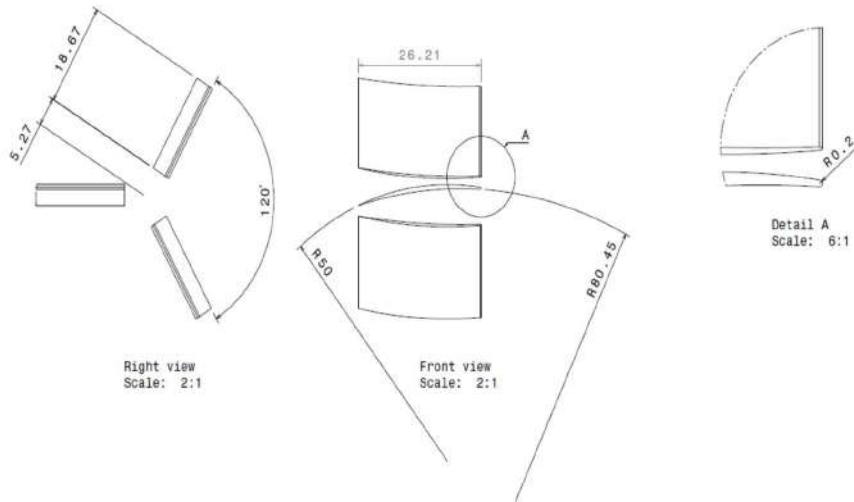


Fig. 4.44 Drawing of Swirling Blades

4.4 Cases taken in CFD results of Auto Swirler:

Three cases at inlet velocity 23m/s, 30m/s and 35 m/s were taken for CFD analysis of auto Swirler. Auto swirler will rotate with the help of air velocity because the inlet air is ultimate source of power of auto swirler.

4.4.1 CFD results at inlet velocity 23 m/s

Velocity Contour shown in Fig. 4.45, for Auto Swirler at air inlet velocity 23 m/s. and maximum velocity found as 55m/s as per contour.

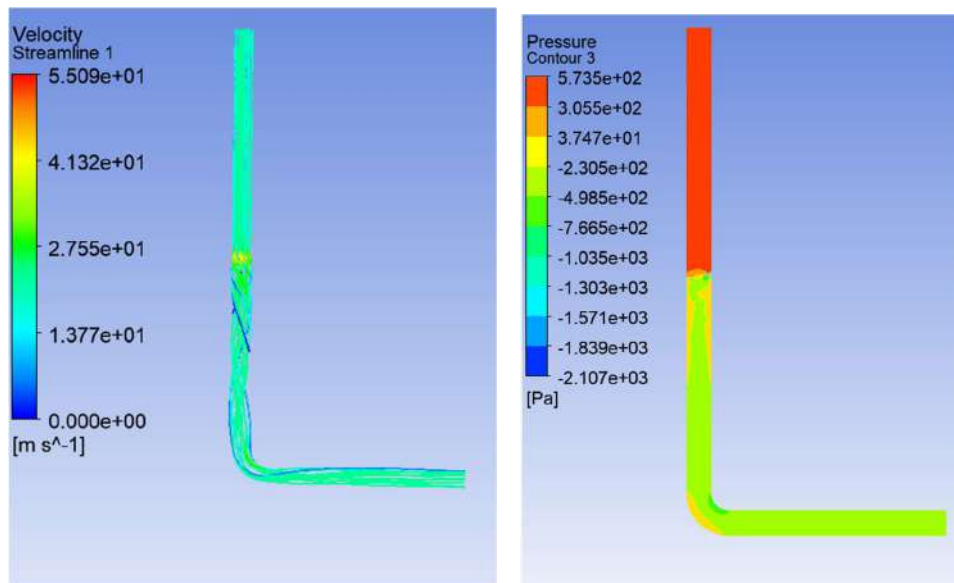


Fig. 4.45 Velocity and pressure contour for auto swirler at air inlet velocity 23m/s

In Fig. 4.46 erosion rate is demonstrated which is found as $6.16 \text{ kg/m}^2\text{s}$ Auto swirler produces the swirling motion in particle hence reduction in erosion rate reported in numerical prediction.

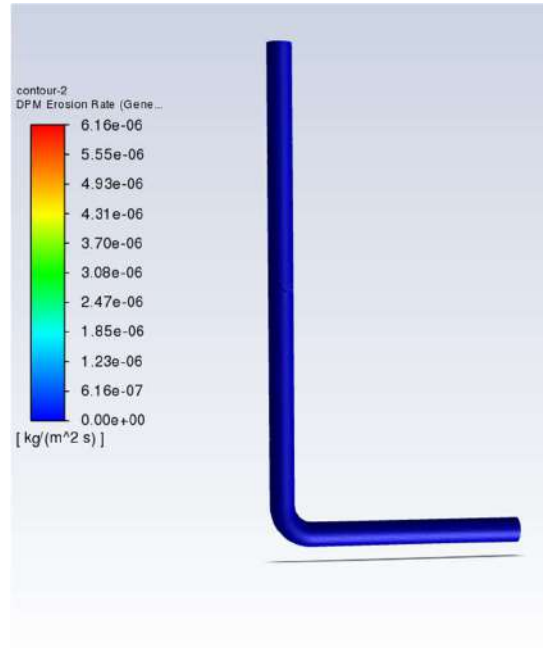


Fig. 4.46 Erosion rate Contour for auto swirler at air inlet velocity 23m/Erosion

In Fig. 4.47 erosion of blades shown and it was found $3.5 \text{ e-06 kg/m}^2\text{s}$ with auto swirler 183rpm.

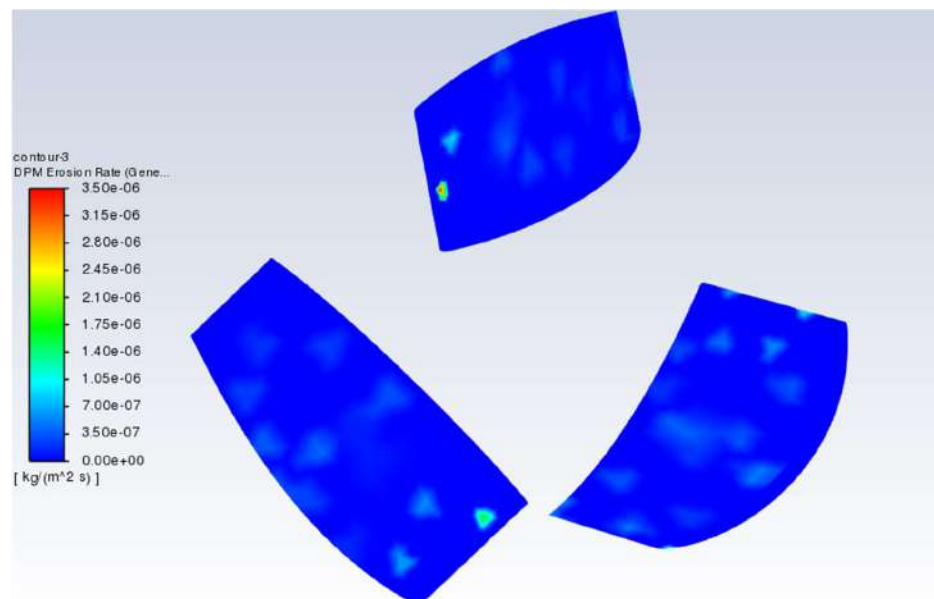


Fig. 4.47 erosion of blades for auto swirler at air inlet velocity 23m/s

4.4.2 CFD results of auto swirler at 30m/sec

In Fig. 4.48, velocity contour shown for the auto swirler at an air inlet velocity of 30 m/s. and found velocity as 49.1 m/s shows increase of velocity. In Fig. 4.48 pressure contour Shown for the auto swirler at an air inlet velocity of 30 m/s., and was found 708.3 Pa.

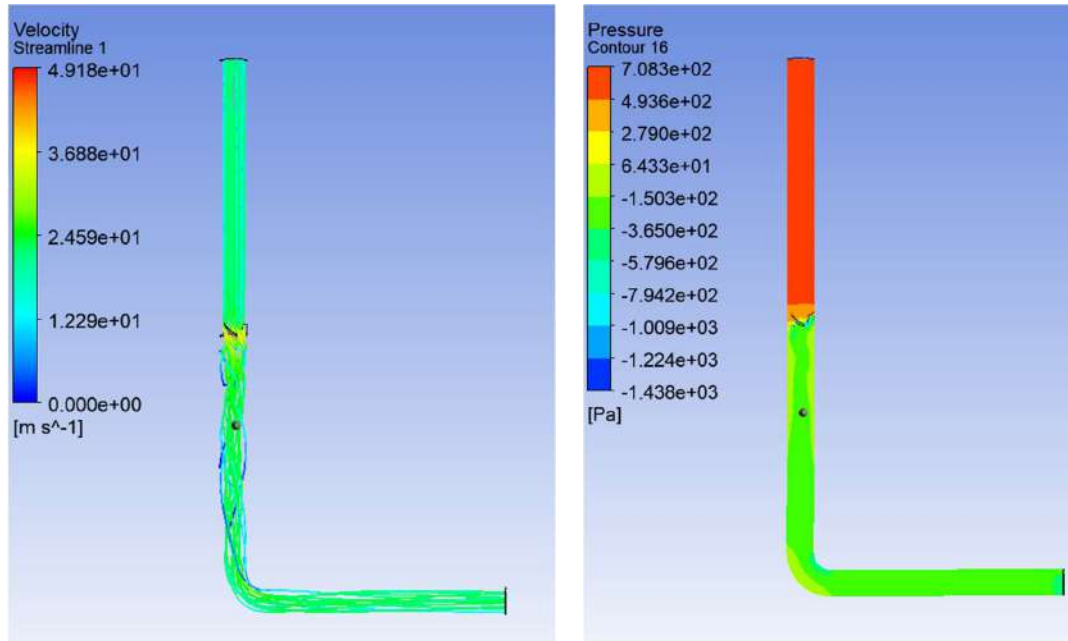


Fig. 4.48 Velocity and pressure contour results at 30m/s

In Fig. 4.49 Erosion on blasé was found as $2.44 \times 10^{-6} \text{ kg/m}^2\text{s}$ at inlet velocity 30m/s. Blade eroded due to striking of particles on the blades produces erosion.

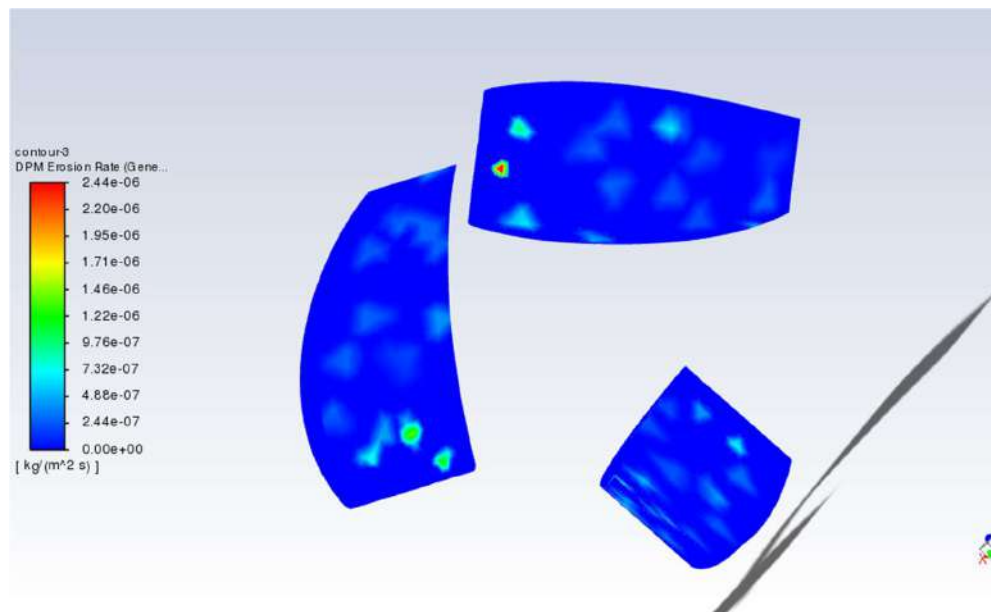


Fig. 4.49 Blade erosion contour at velocity 30m/sec

4.4.3 CFD results of auto swirler at velocity 35m/s

In Fig. 4.50, velocity contour shows velocity 49.68m/s for the auto swirler at an air inlet velocity of 35 m/s, In Fig. 4.50 pressure contour shows pressure 658.8 Pa for the auto swirler at an air inlet velocity of 35m/s.

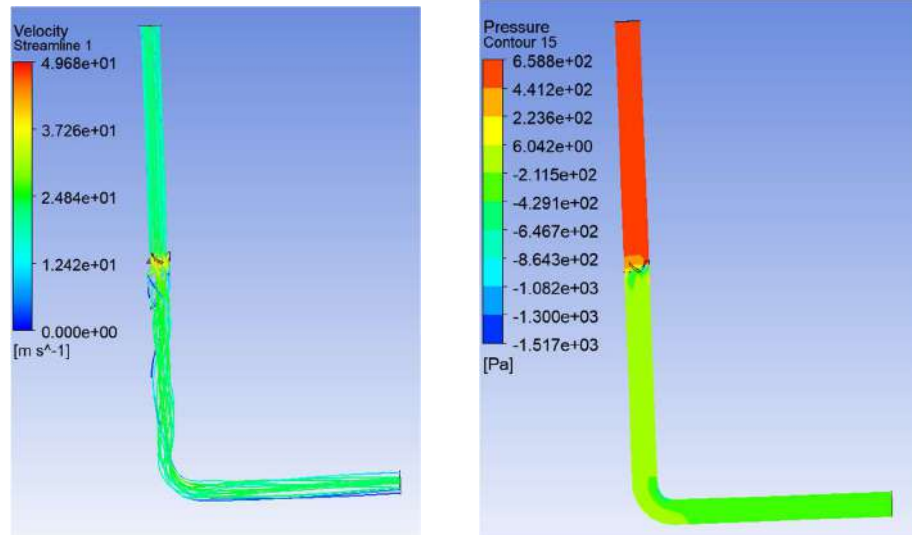


Fig. 4.50 Velocity and pressure contour at 35m/sec

In Fig. 4.51, erosion on swirler blade found as $2.44 \times 10^{-6} \text{ kg/m}^2\text{s}$ at inlet velocity 30m/s. and speed of auto swirler found as 257rpm. This erosion is very less but after a life span auto swirler blades replacement is required.

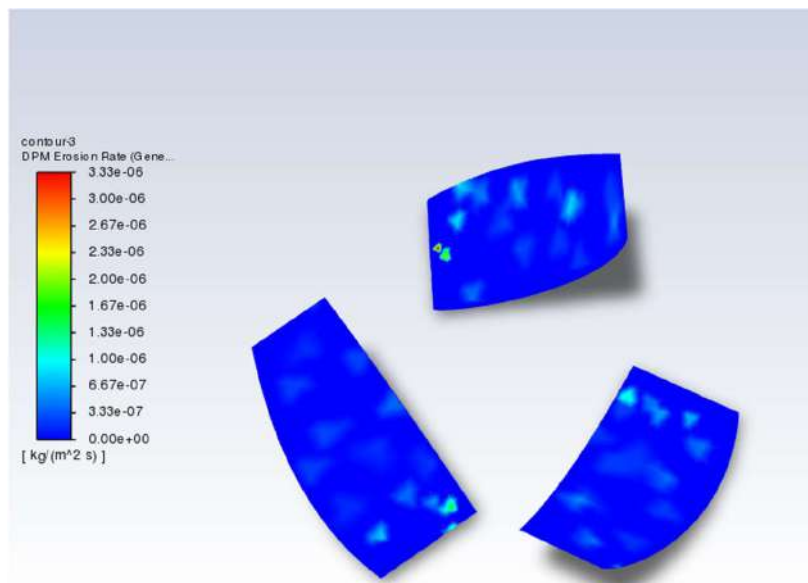


Fig. 4.51 Blade erosion at 35m/s

4.5 Auto swirler results comparison

Compiled results of auto swirler were shown in Table 4.12 shows effectiveness of auto swirler at higher inlet velocity but as bend erosion rate decreases there is increase of blade erosion rate also but found less as compared with overall results.

Table 4.12 Bend erosion and blade erosion results of auto swirler

Velocity	23 m/s	30m/s	35m/s
Blade Erosion (Kg/m2sec)	2.1e-6	2.2e-6	2.67e-6
Blade Erosion Rate (mm/year)	8.436	8.838	10.726
Blade wt loss (g)	4.12	4.31	5.2
Rpm of Swirler	120	183	257
Without Swirler bend erosion rate in mm/year	8	8.5	9.1
Bend Wt Loss (g)	3.90	4.1	4.445
With auto Swirler Erosion Rate in mm/year	6.7	7.1	7.4
Bend Wt Loss (g)	3.3	3.46	3.61
% reduction in bend erosion rate with Auto Swirling	15.38%	15.60%	18.68%

In Fig. 4.52, comparison of experimental data of auto swirler histograms are plotted as inlet velocity increases, it increases rpm of swirler lead to reduction in erosion rate as demonstrated in Fig. 4.52.

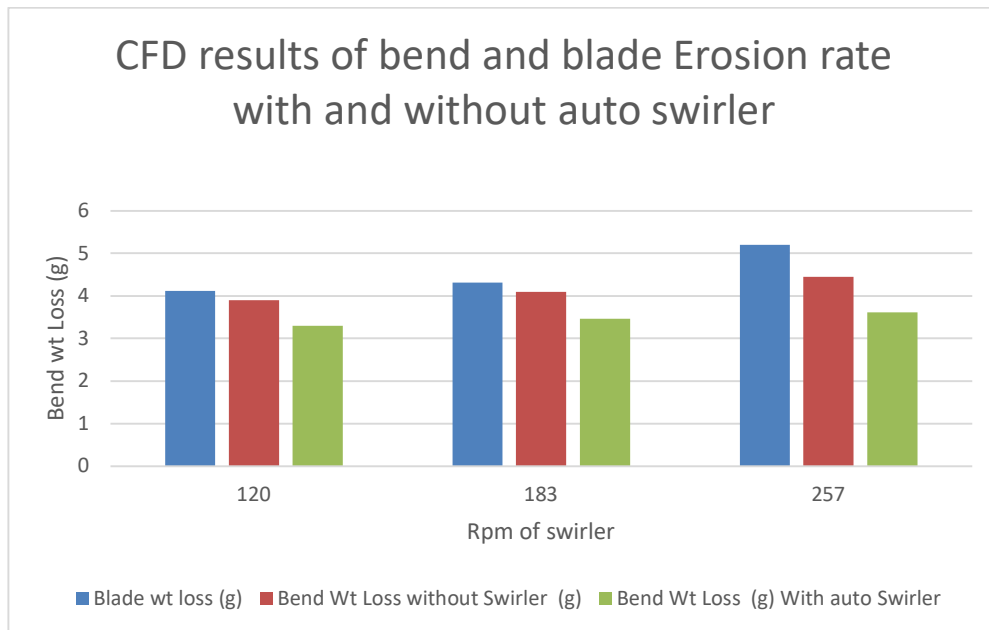


Fig. 4.52 Comparison of experimental results of auto swirler

4.6 Experimental Results of swirling Device:

Experimental Results of bend erosion rate without swirling device, with motor operated swirling device and auto swirling device is compared cfd results in Table 4.13. Experiments shows the exact results of bend erosion while simulation work on boundary conditions. Data is tabulated in Table 4.13.

Table 4.13 Experimental results of motor operated and auto swirl device

Particle Size μm	Bend erosion without Swirling Device (g)		Bend Erosion with motor operated swirling at 35 rpm (g)		Bend Erosion with auto swirling (g)	
	Experiment	CFD	Experiment	CFD	Experiment	CFD
200	4	3.9	2.0	3.3	3	3.1
150	3.3	-	1.4	-	2.6	-
125	2.7	-	0.9	-	2.1	-
% Reduction in Bend Erosion for particle size 200 μm (g)			50%	15.3%	25%	20.51%

In Fig. 4.56 is overall conclusion of this research as all data are plotted here to show result. Comparison of all data shows that CFD results were found validated with experimental results and motor operated swirling device was found most effective.

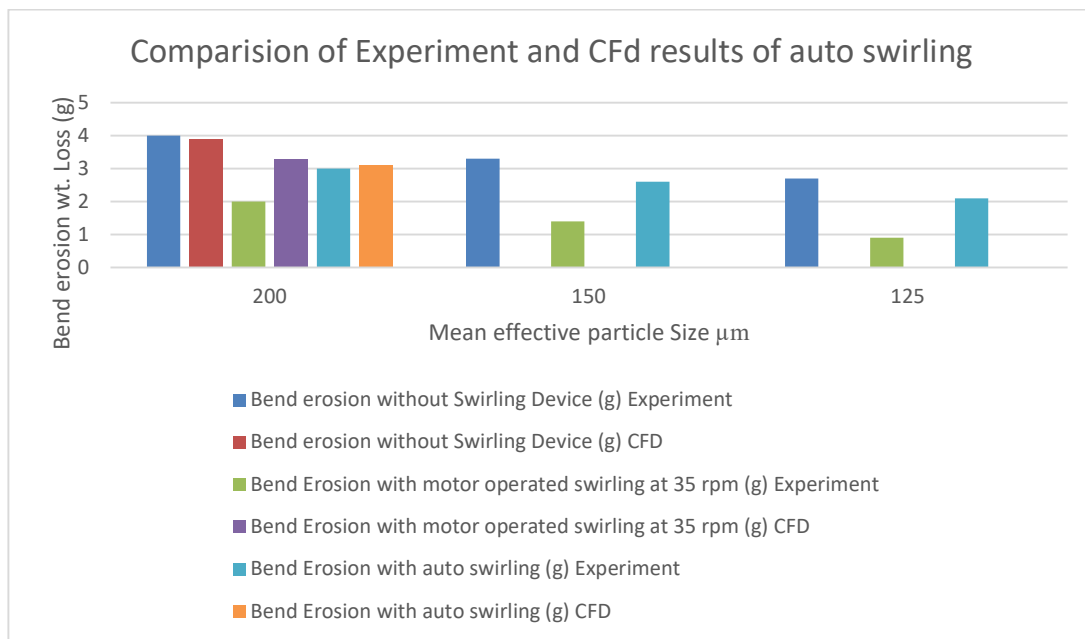


Fig. 4.53 Comparison of bend erosion rate

For conclusions of research results and discussions is very important. Compilation of all data produces the results. Experimental results of bend erosion without swirling, with motor operated swirling device and auto swirling device are analyzed and graphs plotted to withdraw results shows that motor operated swirling device is most efficient and upto 50 % reduction in bend erosion rate was found in results. CFD numerical prediction support the experimental data. Auto swirling device consume the energy of pneumatic conveying system but had issue of blade erosion due choking issues and other experimental drawback, it become less effective than motor operated swirling device. Results are thoroughly discussed and demonstrated in this chapter.

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 CONCLUSIONS

The exhaustive literature review was carried out, and research objectives with methodology have been concluded for the erosive wear study in pneumatic conveying systems. The Investigation of erosive wear in metallic pipe bends was carried out. Auto swirling device was designed and fabricated by 3D printer. The exhaustive experimental and numerical prediction was carried out for pipe bend. Following Conclusions are withdrawn by this research.

- 1 Literature review extracts that erosive wear in pneumatic conveying systems depend on many parameters like velocity, pressure, solid loading ratio etc. Bend Erosion is major issue in pneumatic conveying. Erosion was found as a combination of abrasion, fatigue, plastic deformation in ductile material, brittle fracture, melting of material and super plastic flow as per literature. In present research reverse engineering was utilized to perform wear characterization of failed bend to segregate type of wear in pipe bend.
- 2 Abrasive wear is also a part of erosive wear as both depends on particle size, so POD Tribometer was used to calculate abrasive wear of ms bend material pin was user with different size of emery paper As emery paper effective grit size increases wear rate increases and this wear rate is much higher than the metal-to-metal contact due to pure abrasion of particles creating huge cutting at very small sliding distance of 400m. In these experiments emery paper mean effective particle size is varied from 200 μm , 160 μm and 125 μm and wear rate is maximum in higher grit size. specific wear rate decreases with particle size. As load increases wear rate increases. Three loads 10 N, 20 N and 30 N are studied and found that at 30 N weight loss is maximum for three different discs of emery paper and mild steel pin on POD. As we increase the Sliding Velocity then also wear rate increases the coefficient of friction is about 0.4 between these contacting surfaces it also goes up to 0.7 also as abrasive paper provide more friction. Hence in this study abrasive wear

characterization is done with respect to abrasive grit particles and for mild steel it was found harmful and material change or other contacts can minimize it.

- 3 During macro examination duplex type of failed bend found shows early puncture in bend. Hardness was found. Eroded zone of pipe bends finely polished, on 3 % nital etch, at 100x, matrix reveals pearlitic in ferritic matrix & grain size 7 measured ASTM E-112 because bend got hard due to striking of particles. The Rockwell Hardness Test, specifically scales like HRBW 77 and HRBW 78, indicates a material's ability to resist indentation but bend got punctured due to striking of continuous particle on bend surface.
- 4 Erosion rate increases with increases with increase in Mean Effective Particle (mep) size of Silica Sand and velocity of Particles. These two factors are taken in to consideration in this research.
- 5 Motor operated CFD Results clearly show that as mep increases weight loss in bend increases from 3.9 g to 5.86 g without swirling and with motor operated swirling device we can reduce erosion varies from 19.7% to 50 % due to rpm of swirler from 35 rpm to 100 rpm.
- 6 Motor Operated swirling device CFD analysis was carried out for different bend geometry angles for 15°, 45°, 60°, 90°, and found that at low angles, the erosion rate is less. Reduction in bend erosion was reported nearly 15% for all type of bend angles. Result depicts the maximum erosion rates for a 90° bend without a swirling device and at low impact angles erosion rate is less.
- 7 Turbine like Auto Swirling Device was designed to reduce erosive wear and found that 15 to 20 % reduction in erosive wear which is much lesser than motor operated swirling device.
- 8 The higher erosion rate causes system failure and reduces the life cycle of the system.
- 9 Experiments of Auto swirler, motor operated swirler and without swirler are performed. Auto Swirler was found more effective in experimental results than CFD results as reduction in erosive wear was reported as 20% but motor operated swirling device was more effective.
- 10 Numerical prediction and experiment results validate each other.
- 11 In Auto Swirling Device Erosion is reduced by insertion of blades in pipe but blades also eroded due to silica particles bombardment on the blades.

- 12 Auto swirl founds less effective than motor operated due to material choking in the pipe and swirled bearing got seized by small silica particles. Motor operated swirling device was found very effective with 50 % reduction in erosive wear.
- 13 Complex, three-dimensional flow patterns are a hallmark of fluid-solid motion in a pipe bend. The direction change creates centrifugal forces, which in turn produce secondary flows, including swirl-switching and Dean vortices. This results in high-pressure areas on the outside wall of slurry flows (liquid-solid), which causes significant erosive wear. Model (robustness of free stream) in this research.
- 14 Dean Vortices: In both laminar and turbulent flow, the bend creates two symmetric, counter-rotating vortices that push fluid outside the bend.
- 15 Swirl-Switching: The Dean vortices in turbulent flow become unstable, leading to a "swirl-switching" phenomenon in which the flow alternates between two states on a regular basis. This phenomenon is sometimes characterized as a shift in the dominating vortex that can be unpredictable.
- 16 Secondary Flow & Pressure: High-velocity fluid travels toward the outside wall in a secondary motion caused by the centrifugal force, which raises the pressure on the outer wall and lowers the pressure on the inner wall. It was experienced arrangement of data of inside pressure was not in the setup.
- 17 Swirl Decay: Before returning to a completely formed, straight pipe flow, the swirl created by the bend is extremely tenacious and can go a considerable distance downstream. Due to this choking of material occur and same rectified by opening the whole assembly.
- 18 Motor operated Swirling devices can be used in pharmaceutical industries with suitable material and proper experimentation for contamination before incorporation in those industries.
- 19 Dry powder and dilute phase conveying was experimented in this research.

5.2 RECOMMENDATIONS FOR FUTURE WORK

From this investigation, erosive wear in pipe bend following scope of studies are suggested for further study in future.

- i. To increase the span of swirling area for Auto Swirling device pipe length of 200mm, 300mm and 400mm can be used to study bend erosion rate in pneumatic conveying system.
- ii. Checking of auto Swirling device and motor operated swirling device in actual industrial condition can be further studied and same can be adopted in pneumatic conveying systems. .
- iii. As velocity increases pressure drops create choking issues in pneumatic conveying can be further studied.
- iv. Light weight metal casted auto swirl device can have further scope of research
- v. Detachable blades in auto swirler have further scope.
- vi. Study of swirling device in dense phase conveying can be further studied.
- vii. Camera inside the pipe line as well as in bend can be placed for clear demonstrations of the Swirl flow.
- viii. Pressure as well as velocity recording device should be incorporated in setup to find real values of parameters.
- ix. Pneumatic conveying systems can be studied for transportation of cattle field from field to storage rooms.
- x. Scope of pneumatic conveying in agriculture sector can be further investigated.

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Appendix 1

Derivation of SST k omega model in ansys

The Shear Stress Transport (SST) $k-\omega$ turbulence model, developed by Florian Menter in 1994, is a hybrid Reynolds-Averaged Navier-Stokes (RANS) model used in ANSYS Fluent and CFX. It is not a single derivation but rather a sophisticated combination of the Wilcox $k-\omega$ model (for near-wall regions) and a transformed $k-\epsilon$ model (for free-stream regions). ⁸

The model's derivation is based on the following key components: ⁸

- **Blending function (F_1):** A function that smoothly transitions between the two models.
- **Shear-Stress Transport:** A modification to the turbulent viscosity to account for the transport of the turbulent shear stress.
- **Production limiter:** Prevents the build-up of excessive turbulent kinetic energy in stagnation regions.
- **Cross-diffusion term:** Added to the ω -equation to improve accuracy. ⁸

1. Model blending using the Blending Function (F_1)

The core of the SST model lies in its ability to combine the strengths of two separate models. This is achieved by a blending function, F_1 , which ranges from 0 to 1. ⁸

- **Near-wall regions ($F_1 \rightarrow 1$):** The model uses the Wilcox $k-\omega$ formulation, which is accurate and robust in the viscous sub-layer and buffer layer.
- **Free-stream regions ($F_1 \rightarrow 0$):** The model switches to a $k-\epsilon$ formulation, which is less sensitive to free-stream boundary conditions and performs well in far-field flows. ⁸

This blending is performed for each term in the transport equations for k and ω . The generic blending formula for a coefficient ϕ is given as:

$$\phi = F_1 \phi_1 + (1 - F_1) \phi_2$$

Here, the subscript 1 represents coefficients from the $k-\omega$ model, and the subscript 2 represents coefficients from the transformed $k-\epsilon$ model. ⁸

The blending function, F_1 , is designed as a hyperbolic tangent function, which ensures a smooth transition and is dependent on the distance from the wall. ⁸

2. Shear Stress Transport (SST) formulation

A key modification in the SST model is the improved formulation for turbulent viscosity (μ_t), which accounts for the transport of the principal shear stress. The SST model's μ_t is defined as:

$$\mu_t = \frac{\rho a_1 k}{\max(a_1 \omega, S F_2)}$$

⁸

- k is the turbulent kinetic energy.
- ω is the specific dissipation rate.

The SST model solves two transport equations for k and ω . These equations are blended between the k - ω and k - ϵ formulations. [Ⓔ]

Transport equation for Turbulent Kinetic Energy (k)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] + \tilde{P}_k - \rho \beta^* k \omega$$

- LHS: The transient and convective transport of k .
- First term on RHS: The diffusive transport of k . σ_k is the turbulent Prandtl number for k , blended from σ_{k1} and σ_{k2} .
- $\tilde{P}_k$: The production of turbulent kinetic energy, which includes a limiter to prevent overproduction.
- $\rho \beta^* k \omega$: The dissipation of turbulent kinetic energy, where β^* is a constant. [Ⓔ]

Transport equation for Specific Dissipation Rate (ω)

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + \rho \gamma \tilde{S}^2 - \rho \beta \omega^2 + 2\rho(1 - F_1) \frac{\sigma_{\omega 2}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

- LHS: Transient and convective transport of ω .
- First term on RHS: Diffusive transport of ω . σ_ω is blended from $\sigma_{\omega 1}$ and $\sigma_{\omega 2}$.
- $\rho \gamma \tilde{S}^2$: Production of ω , where $\tilde{S}$ is related to the strain rate.
- $\rho \beta \omega^2$: Dissipation of ω .
- Cross-diffusion term: This is a key modification, included only when the k - ϵ model is active ($F_1 \rightarrow 0$). It enhances the model's accuracy away from the wall. [Ⓔ]

4. Ansys implementation

In ANSYS Fluent, the SST k - ω model is implemented as a standard turbulence model based on Menter's original work. The software solves the RANS equations, with the turbulent viscosity and other terms computed using the SST transport equations. The robust blending function and shear stress transport make it a highly accurate and reliable model for a wide range of applications, including those with adverse pressure gradients, separation, and impinging jets. [Ⓔ]

RESEARCH PUBLICATIONS:

List of Papers Published in SCI/SCIE/Scopus/Indexed Journals:

- 1 Yadav, B. S., Singh, R. C., & Chaudhary, R. (2020, April). Experimental investigations for erosive wear of Mild Steel Pipe bends at different positions in Pneumatic Conveying System (PCS). In IOP Conference Series: Materials Science and Engineering (Vol. 804, No. 1, p. 012008). IOP Publishing.
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- 1 Yadav, B. S., Singh, R. C., & Chaudhary, R. (2020, April). Experimental investigations for erosive wear of Mild Steel Pipe bends at different positions in Pneumatic Conveying System (PCS). In IOP Conference Series: Materials Science and Engineering (Vol. 804, No. 1, p. 012008). IOP Publishing.
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CFD MODELLING OF SWIRLING DEVICE TO STUDY BEND EROSION RATE AT DIFFERENT BEND ANGLES IN PNEUMATIC CONVEYING SYSTEM

Reference NO. IJME 1342, DOI: 10.5750/ijme.v1i1.1342

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SUMMARY

Bend Erosion problems were found mostly common in pneumatic conveying plants. Swirling of particles before striking the bend has been noted as the best solution to minimize bend erosion rate. CFD k-w model in Ansys was applied to analyze mild steel bend erosion in the pipeline by pneumatically conveyed particles with a motor-operated swirling device. A part of the pipe before the bend is rotated at different velocities in different elbow geometries from 15° to 90° elbows. A combination of Eulerian and Lagrangian methods were utilized to track particles. Mathematical modelling of the swirling of particles on bent surfaces is taken into consideration with different elbow angle. The bend erosion rate was mitigated due to the swirling of particles. Different velocities and parameters are taken to evaluate the results. At different bend angles erosion rate is different and the swirling device minimizes the bend erosion rate.

KEYWORDS

Swirling device, Mean effective particle (mep) size, Erosion rate

NOMENCLATURE

ν	Kinematic viscosity (N s m^{-2})
ρ	Density of water (kg m^{-3})
P	Pressure (N m^{-2})
v	Velocity (m/sec)
m	Mass Flow Rate kg/sec
ϕ	Form Factor
PCS	Pneumatic Conveying System
mep	Mean Effective Particle Size of Silica, μm

1. INTRODUCTION

Different types of bends like Metric (M) bends, sharp bends (S), and other types of different angle bends are used to convey powder-type particles. G. Arun [1] discussed the comparison of 90° S and M bends for erosion rate. Differences in the swirl flow induced at the pipe assembly's outlet were reported. Computational Fluid Dynamics (CFD) modeling on Ansys has been utilized to find the bend erosion rate in a pneumatic conveying system. A computational fluid dynamics-based erosion prediction model and its application to 3D double elbows were presented by Li et al. [2]. The numerical flow visualization results help in understanding the detailed flow characteristics in the 90°-S

and 90°-M pipe bends. Wall shear stresses were observed in S bend pipe assemblies because of abrupt sharp flow turning which produces higher pressure drops. It is evident that several experimental and computational/numerical studies were conducted in smooth pipe bends with constant radii. The appropriate bend geometric parameters were found and reported using computer simulations. Jiang et al. [3] used the volume of fluid (VOF) model in conjunction with the continuous surface stress (CSS) model to simulate the core annular of non-Newtonian oil and water flow through the rectangular return bends. Conversely, mitered bends created by combining two or more pieces of sheet metal pipe segments are frequently utilized in a variety of industrial settings when a sharp turn in the flow is required. When there is not enough room for a smooth, constant-radius bend, these mitered bends are utilized. Hiroshi and associates using turbulent flow through a 90° pipe elbow in a range of moderately high Reynolds numbers between 14,000 and 34,000 by wall-resolved large-eddy simulation (LES) and multiple Reynolds-averaged Navier-Stokes (RANS) models, studied computationally to demonstrate advantages and disadvantages of different computational methods for the considered case. The RANS models utilized in this investigation comprise the fundamental low Reynolds number k-model [4]. A laminar non-Newtonian pseudoplastic power law model was employed by Bandyopadhyay et al. [5] to simulate non-Newtonian liquid

CFD MODELLING OF SWIRLING MECHANISM TO REDUCE EROSION OF PIPE BEND IN PNEUMATIC CONVEYING SYSTEM

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SUMMARY

Dry powders mixed with air transportation had bend erosion issues. CFD analysis by Shear-Stress Transport (SST) k- ω Model within Ansys was used to conduct a comprehensive numerical analysis of particle erosion within a 90° mild steel pipe bend in Pneumatic Conveying System. Part of the conveying pipe rotation achieved with the external motor swirling device was used to create swirling of particle before bend. Different-sized sand particles at different rpm were tested with and without a swirling device. Reduction in erosion rate of pipe bend carries significant implications, notably an extension of the system's operational lifespan. Reduction in erosion rate reports an impressive increase of 50% bend lifespan at higher RPM levels of the swirling device. The results underscore the effectiveness of this device in mitigating erosion, with significant implications for enhancing the longevity and reliability of bend life in piping systems of Pneumatic Conveying applications.

KEYWORDS

Bend, Swirling Device, Mean Effective Particle (mep) Size, Erosion Rate

NOMENCLATURE

ν	Kinematic viscosity (N s m^{-2})
ρ	Density of water (kg m^{-3})
P	Pressure (N m^{-2})
v	Velocity (m/sec)
m	Mass Flow Rate kg/sec
ϕ	Form Factor
PCS	Pneumatic Conveying System
mep	Mean Effective Particle Size of Silica, μm

According to Singh et al. [1], in design calculations, the flow velocity should be the most important factor to consider. The “erosional velocity” should be established based on the pipeline flow velocity, denoted as V_e [feet/sec]. This value indicates the velocity threshold at which erosion is likely to occur, serving as a marker for the velocity level where erosion could potentially take place.

$$V_e = \frac{C}{\sqrt{\rho}} \quad (1)$$

The variable C is an empirical constant, while ρ signifies the density of the fluid combination, measured in $[\text{lbs/ft}^3]$.

Nonetheless, according to Salama et al. [12], erosion typically occurs only at very high velocities in solids-free fluids.

These guidelines are based on the work of Salama et al. [12], and they provide insights into selecting the appropriate value of C for different scenarios. The constant C is crucial for calculating particle erosion in pipe bends, as outlined in Ababaei et al. [2].

According to Durate et al. [3], the preferred approach for complex piping layouts or scenarios where erosion location is of utmost significance is to perform Computational Fluid Dynamics (CFD) erosion simulations.

1. INTRODUCTION

In the complex landscape of particle erosion, several factors play pivotal roles in determining erosion rates, as outlined in PCS [1]. These factors, including particle properties (size, hardness, velocity), fluid characteristics, and surface geometries, collectively influence the erosive behavior within oil and gas production systems. Comprehensive consideration of these factors is essential for engineering robust solutions that safeguard system integrity and minimize bend erosion-related challenges, ensuring the reliability and longevity of these critical systems.”

The angle at which sand particles impact is a significant factor in surface erosion. Considerable research has been carried out in this field, leading to the creation of both theoretical and empirical erosion models.

Experimental investigations for erosive wear of Mild Steel Pipe bends at different positions in Pneumatic Conveying System (PCS)

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Abstract. Pharmaceutical and chemical industries have been using transportation of various material/powder through pipes. The bend was punctured in the conveying system during the flow of material and finally stops the production. The scientists and researchers are working on material and mechanism to reduce the material loss of the bends. An experimental investigation have been carried out for erosive wear in pipe bends of a pneumatic conveying pipe line. Six bends has been considered for the investigation of wear at 90° from rotary feeder to air filter. The Comparison of erosive wear was investigated for all six pipe bends. The bend 2 was the most critical place in the pipeline. Other five bends had less erosion than the bend 2 due to maximum velocity of the flow.

Keywords: Erosive wear, Sieve Analysis, Pipe bend, Mean particle size, calibration of load cell, solid loading ratio, weight of silica sand circulated etc.

1. Introduction:-

Pneumatic conveying is widely used for transportation of varieties of dry powders and granular solids through pipelines and bends using high pressure gas/air. It is a frequently used method of material transport for short distances in industries/plants. It offers flexibility in terms of pipeline routing as well as dust minimization.

It is worth mentioning for information that about 80% of pneumatic conveying in industries is done in dilute phase which use relatively large amount of air/gas to achieve high particle velocity to stay away from trouble of choking in the pipelines. However, in many applications higher particle velocity lead to excessive levels of particle attrition and wear of pipelines. Moreover, bends are known to be responsible for various problems such as high pressure loss, product segregation and degrading, roping, and erosive wear. It is needed to mention here that one of the ways to reduce the erosive wear of pipe bends is to use proper bend materials and prolong the life of bends. However, another good approach may be to design different type of bends for manipulating the direction of particle impact at the bends, which can lead to reduction in erosion and choking in the pipe bends and pipelines, respectively.

In pneumatic conveying pipelines, the particles are free to roll, slide and impact. Thus, surface of pipe bend is subjected to complex mechanism of material removal. This is known as wear of the bend's



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BRIEF PROFILE

I, Bharat Singh Yadav, completed B. Tech in Mechanical Engineering from Kurukshetra University, Kurukshetra, Haryana, India, and M.Tech in Industrial Tribology and Mechanical Maintenance Engineering (ITMEC) from the Indian Institute of Technology (IIT), Delhi, India. Currently, I am working as a Lecturer in Mechanical Engineering in the Department of Mechanical Engineering at DSEU Pusa Campus-1 (Pusa Institute of Technology), formerly Pusa Polytechnic. I have enrolled for a Ph.D. in the Department of Mechanical Engineering at Delhi Technological University, Delhi-42, (India) under the supervision of Prof. Rajiv Chaudhary and Prof. R.C. Singh.