A STUDY ON THE FLOW OF MULTI-SIZED PARTICULATE SOLID-LIQUID MIXTURES IN HORIZONTAL PIPELINES

By
RAKESH MISHRA
Department of Applied Mechanics

Submitted
in fulfilment of the requirement for
the degree of
DOCTOR OF PHILOSOPHY

to the
INDIAN INSTITUTE OF TECHNOLOGY, DELHI
JULY, 1996
DEDICATED TO MY PARENTS

Father: Sri. R. P. Mishra

Mother: Smt. P. K. Mishra
CERTIFICATE

This is to certify that the thesis entitled A STUDY ON THE FLOW OF MULTISIZED PARTICULATE SOLID-LIQUID MIXTURES IN HORIZONTAL PIPELINES being submitted by Rakesh Mishra to the Indian Institute of Technology, Delhi (India) for the award of the Degree of Doctor of Philosophy in Applied Mechanics is a record of bonafide research work carried out by him under our supervision and guidance. The thesis in our opinion, has reached the requisite standard fulfilling the requirement of Doctor of Philosophy Degree.

The research report and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.

(S.N. Singh)  
Professor  
Deptt. of Applied Mechanics  
Indian Institute of Technology  
New Delhi- 110016

(V. Seshadri)  
Professor  
Deptt. of Applied Mechanics  
Indian Institute of Technology  
New Delhi- 110016
ACKNOWLEDGEMENT

It is my privilege to have worked under the worthy guidance of my esteemed supervisors Prof. V. Seshadri and Prof. S.N. Singh. Words are inadequate to acknowledge the great care and interest taken by them in all aspects of the present work. It is a great pleasure for me to record my deep sense of gratitude to them for their valuable guidance, encouragement and friendly discussions during the course of this work. My association with them throughout the research activity was a great process of learning.

The assistance extended by the wonderful staff of the Fluid Mechanics Laboratory (where the experiments were conducted) namely, Mr. Sita Ram, Ram Sarup, Onkar Singh, R.P. Bhogal, Roop Ram, Diwan Singh and Sher Singh is gratefully acknowledged. The help of Mr. Sita Ram and Mr. Onkar Singh was invaluable during the fabrication and experimental work. Thanks are also due to staff of other laboratories of the Applied Mechanics Department and Instrument Design and Development Centre of the Institute for their help.

I am grateful to my parents, brothers Rajesh and Manish, and sister Neelam for their continuous moral support and encouragement during the course of this work. My wife Sabita and son Shashwat deserve a special mention for making my stay at I.I.T., Delhi comfortable and enjoyable. They willingly endured the hardship during my preoccupation with this work and also supported me in all possible ways. Without their help thesis would not have reached in its present form.

I acknowledge the support provided by the Principal, Motilal Nehru Regional Engineering College, Allahabad by sponsoring me under the Quality Improvement
Program. Acknowledgements are also due to Ministry of Human Resource Development, Govt. of India for providing financial support under Quality Improvement Program.

I express my gratitude to Prof. Y. Nath and Dr. Ratan Mohan for help and encouragement provided during the course of present work.

Thanks are also due to my friends Dr. Bireswar Majumdar, Sanjeev Bharani, Mukul Shukla, S.G. Tripathi, Mahendra Singh and Mr. B.K. Gandhi for their help and moral support at various stages of the present work.

Finally I thank all who have directly or indirectly helped me during the course of the present work.

(RAKESH MISHRA)
ABSTRACT

Slurry pipelines are being extensively used for transporting solid materials in bulk quantities over large distances in various industries. The present knowledge of the flow mechanics of solid-liquid mixtures is far from complete. There is substantial empiricism in the design methodologies for slurry pipelines used for multi-sized particulate solid-liquid mixtures. The present study is aimed towards the better understanding of different facets of the flow of multi-sized solid-liquid mixtures. Based on the literature review the scope of the present study was envisaged. Different aspects of the work carried out are outlined below.

(i) Determination of concentration and velocity fields in pipeline for multi-sized particulate slurry flow.

(ii) Design and development of wear resistant bends and to investigate the wear and flow characteristics in the conventional and modified bends.


The experimental studies have been carried out in a pilot plant test loop existing in the Fluid Mechanics Laboratory of the I.I.T. Delhi. Special fixtures were fabricated to carry out the concentration and velocity field studies. Modified bends were also fabricated and installed in the same loop to study the wear and flow characteristics in these bends.

Flow of solid-liquid mixtures in pipelines is generally in heterogeneous regime. Currently, the concentration is assumed to be constant along horizontal chords which may not be really true. The particle sizes vary over three orders of magnitude for multi-sized slurries and hence are affected differently by the flow parameters. In the present study, the concentration distribution and the distribution of different particle
sizes has been measured experimentally along six horizontal chords at different
heights from bottom of the pipe to establish the effect of flow velocity and efflux
concentration. The study has revealed that the larger size particles are non-uniformly
distributed both along the vertical and the horizontal planes. The finer particles
however are distributed uniformly throughout the pipe cross-section.

Reported studies on the velocity field in a pipeline of a multi-sized slurry flow
are limited. A two-hole offset probe with a modified differential pressure measuring
system has been used in the present study for the determination of the velocity field
for the flow of multi-sized particulate solid-liquid mixtures in a pipeline over a wide
range of efflux concentrations and flow velocities. Velocity measurement along four
diametrical planes namely, vertical, horizontal and two diagonal planes (± 45° planes)
show that velocity profiles along vertical plane are asymmetric with peak velocity
point displaced towards the top wall. Velocity profiles were also asymmetric along the
two 45° planes with extent of asymmetry being less than the vertical plane. Along the
horizontal plane, the velocity profile was seen to be symmetric.

An attempt has been made to develop wear resistant bends for the flow of
solid-liquid mixtures in a pipeline. The two bends designed and fabricated are
diverging-converging in shape and have same inner radius as the conventional bend
but gradually varying area of cross-section. The area of cross-section of these bends
increased from inlet to the centre and then decreased from centre to the outlet. The
area ratios of the two bends were 1.5 and 2 respectively. Extensive wear tests have
been performed on three bends namely, conventional bend and two modified bends.
Experiments have shown that modified bend with an area ratio 2 is less prone to
wear as compared to the other two bends. The maximum wear in area ratio 2 bend
is even less than the maximum wear in straight pipe. Solid distribution across the
middle plane of the bends was also measured to establish dependence of wear on solid distribution pattern. Analysis of the data has shown that solids are more uniformly distributed in modified bends and there is no tendency of the particles to move out. It is also observed that modified bends are less susceptible to deposition as compared to straight pipe and conventional bend. Pressure drop studies on these bends has shown that pressure drop across modified bends is higher in comparison to the conventional bend.

Accurate prediction of flow parameters helps in designing a slurry pipeline optimally. In present study, different models available in literature for prediction of flow parameters such as pressure drop, concentration profile, velocity profile and wear rate have been identified and their applicability to the flow of multi-sized slurries analyzed. Comparison between predicted and author's data showed discrepancies which prompted author to attempt modifications in some of the existing models. Suitable modifications were incorporated to increase the accuracy and range of applicability of such models. One of the important modification incorporated is the use of static settled concentration in place of maximum packing concentration as a correlating parameter, since for a multi-sized slurry static settled concentration can be determined more easily and accurately as compared to maximum packing concentration. Experiments were conducted to establish the dependence of static settled concentration on particle size and specific gravity. Results show that static settled concentration increases with increase in particle size and decreases with increase in particle density. Based on the results, an empirical correlation has been proposed for predicting static settled concentration of multi-sized slurries using weighted mean diameter as the representative particle size.
CONTENTS

CERTIFICATE (i)
ACKNOWLEDGEMENT (ii)
ABSTRACT (iv)
CONTENTS (vii)
LIST OF FIGURES (xiv)
LIST OF TABLES (xxxii)
LIST OF PHOTOGRAPHS (xxxii)
NOMENCLATURE (xxxiii)

CHAPTER 1- INTRODUCTION 1-14
1.1 HYDRAULIC TRANSPORTATION OF SOLIDS AND ITS RELEVANCE 1
1.2 MECHANICS OF TRANSPORTATION OF SOLIDS AND FLOW REGIMES IN SOLID-LIQUID FLOW. 2
1.3 HYDRAULIC DESIGN OF THE SLURRY PIPELINE. 5
  1.3.1 Important Design Parameters 5
  1.3.2 Selection of Design Parameters 7
1.4 MOTIVATION FOR THE PRESENT STUDY 13

CHAPTER 2- LITERATURE REVIEW 15-53
2.1 PRESSURE DROP IN STRAIGHT SLURRY PIPELINES 15
2.2 CONCENTRATION FIELD IN SLURRY PIPELINE 21
  2.2.1 Overall Concentration Field in a Slurry Pipeline 21
  2.2.2 Particle Size Distribution 30
2.3 VELOCITY DISTRIBUTION IN A SLURRY PIPELINE 32
2.4 WEAR RATE IN STRAIGHT SLURRY PIPELINES 40
2.5 STUDIES ON FLOW CHARACTERISTICS AND WEAR IN BENDS 44
2.6 STATIC SETTLED CONCENTRATION OF SLURRIES 50
2.7 SCOPE OF THE PRESENT STUDY 51

CHAPTER 3- EXPERIMENTAL SET-UP AND INSTRUMENTATION 54-66
3.1 PILOT PLANT TEST LOOP 54
   3.1.1 Test Bends 56
   3.1.2 Fixtures for Concentration Field Determination 56
   3.1.3 Test Section for the Measurement of Velocity Distribution in the Slurry Flow. 56
3.2 INSTRUMENTATION 57
   3.2.1 Flow Rate Measuring Device 57
   3.2.2 Concentration Distribution Measurement 57
   3.2.3 Pressure Drop Measurement 58
   3.2.4 Velocity Measurement 59
   3.2.5 Wear Rate Measurement 59
3.3 BENCH SCALE TESTS 60
   3.3.1 Particle Size Distribution 60
   3.3.2 Specific Gravity of Solids 61
   3.3.3 Static Settled Concentration 61
   3.3.4 Specific Gravity of Slurry at Different Concentrations 61
3.4 RHEOLOGICAL TESTS 62
CHAPTER 4 - CONCENTRATION FIELD IN A PIPELINE
TRANSPORTING MULTI-SIZED PARTICULATE SLURRIES

4.1 TEST FIXTURE FOR THE DETERMINATION OF CONCENTRATION FIELD

4.2 MATERIAL PROPERTIES
4.2.1 Specific Gravity of Solid Particles
4.2.2 Specific Gravity of Slurry
4.2.3 Particle Size Distribution
4.2.4 Settling Characteristics of the Fresh Slurry
4.2.5 Rheological Parameters of the Slurry

4.3 RANGE OF PARAMETERS

4.4 EXPERIMENTAL DATA AND RESULTS
4.4.1 Overall Concentration Field
4.4.2 Concentration Fields Corresponding to Different Particle Sizes in Multi-sized Slurry Flow
4.4.3 Vertical Concentration Gradients along Mid-vertical Plane
4.4.4 Variation of Bottom Concentration
4.4.5 Vertical Concentration Gradients of Different Particle Sizes

4.5 CONCLUDING REMARKS
CHAPTER 5-

VELOCITY FIELD IN MULTI-SIZED SLURRY FLOWS
THROUGH HORIZONTAL PIPES

5.1 INSTRUMENTATION FOR THE MEASUREMENT OF LOCAL
SLURRY VELOCITY.

5.1.1 Details of the Velocity Probe and Pressure Measuring System. 126
5.1.2 Calibration of the Probe. 129

5.2 VELOCITY MEASUREMENT IN SOLID-LIQUID FLOW.

5.2.1 Test Section 131
5.2.2 Range of Parameters 132
5.2.3 Accuracy of the Measurements 132

5.3 RESULTS AND DISCUSSION

5.3.1 Mixture Velocity Profiles 135
5.3.2 Velocity Contours 140
5.3.3 Special Features of Velocity Distribution in Slurry Pipe Flow 141

5.3.3.1 Asymmetry in velocity profile along mid-vertical plane 142
5.3.3.2 Variation of local maximum velocity as a function of concentration and flow rate 144
5.3.3.3 Location of maximum velocity as a function of efflux concentration and flow rate 145
5.3.3.4 Variation of velocity at bottom and top of pipe with respect to efflux concentration and flow rate 146
5.3.3.5 Prediction of total flow rate from the velocity

x
profile in the mid-vertical plane 148
5.3.3.6 Velocity profile in the mid-horizontal plane 149
5.4 CONCLUDING REMARKS 150

CHAPTER 6. DEVELOPMENT OF WEAR RESISTANT PIPE BENDS FOR SLURRY FLOWS 181-273

6.1 DESIGN AND DEVELOPMENT OF DIVERGING-CONVERGING BENDS 181
6.2 DETAILS OF THE TEST FIXTURE FOR MEASURING CONCENTRATION FIELD AND WEAR RATE. 183
6.3 MATERIAL USED AND RANGE OF PARAMETERS 184
6.4 WEAR RATE CHARACTERISTICS OF BENDS 185
   6.4.1 Wear Rate in Conventional Bend 186
   6.4.2 Wear Rate in Bend with Area Ratio 1.5 187
   6.4.3 Wear Rate in the Bend with Area Ratio 2.0 188
6.5 RELATIVE WEAR IN BENDS 190
6.6 CONCENTRATION FIELD IN BENDS 193
   6.6.1 Concentration Field in Conventional Bend 193
   6.6.2 Concentration Field in Bend with Area Ratio 1.5 199
   6.6.3 Concentration Field in Bend with Area Ratio 2.0 202
6.7 FLOW BEHAVIOR IN BENDS NEAR DEPOSITION VELOCITY IN THE STRAIGHT PIPE 207
6.8 PRESSURE DROP CHARACTERISTICS OF CONVENTIONAL AND WEAR RESISTIVE BENDS 210
6.8.1 Experimental Program and Range of Parameter. 211
6.8.2 Pressure Drop Characteristics of Bends. 211
6.8.3 Relative Pressure Drop for Conventional as well as Wear Resisive Bends. 215
6.8.4 Bend Loss Coefficients for Conventional as well as Wear Resistive Bends. 218

6.9 CONCLUDING REMARKS 219

CHAPTER 7 PREDICTION OF FLOW PARAMETERS IN MULTI-SIZED PARTICULATE SLURRY FLOW THROUGH PIPES 274-333

7.1 PARAMETERS AFFECTING THE STATIC SETTLED
CONCENTRATION OF MULTI-SIZED PARTICULATE SLURRIES 275
7.1.1 Physical Properties of the Materials Used 276
7.1.2 Experimental Procedure and Range of Parameters 277
7.1.3 Results and Discussion 279

7.2 PREDICTION OF PRESSURE DROP IN A SLURRY PIPELINE 284
7.2.1 The Two Layer Model Proposed by Gillies et al. [33] 285
7.2.2 Computational Procedure 289
7.2.3 Pressure Drop Prediction under Various Flow Conditions using Two Layer Model. 291
7.2.4 Modifications in the Two Layer Model 293
7.2.5 Results and Discussion 294

7.3 PREDICTION OF CONCENTRATION DISTRIBUTION USING MODIFIED KARABELAS MODEL 294

xii
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3.1</td>
<td>Modified Karabelas Model [35]</td>
<td>295</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Computational Procedure</td>
<td>299</td>
</tr>
<tr>
<td>7.3.3</td>
<td>Comparison of Experimental Data with Predicted Results</td>
<td>300</td>
</tr>
<tr>
<td>7.4</td>
<td>PREDICTION OF VELOCITY FIELD IN SLURRY PIPELINES</td>
<td>301</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Details of the Model for Velocity Distribution Prediction as</td>
<td>302</td>
</tr>
<tr>
<td></td>
<td>Proposed by Roco and Shook [78]</td>
<td></td>
</tr>
<tr>
<td>7.4.2</td>
<td>Computational Procedure</td>
<td>307</td>
</tr>
<tr>
<td>7.4.3</td>
<td>Comparison between Predicted and Experimental Results.</td>
<td>308</td>
</tr>
<tr>
<td>7.4.4</td>
<td>Modifications Proposed</td>
<td>309</td>
</tr>
<tr>
<td>7.4.5</td>
<td>Results and Discussion</td>
<td>310</td>
</tr>
<tr>
<td>7.5</td>
<td>PREDICTION OF WEAR RATE IN SLURRY PIPELINES</td>
<td>311</td>
</tr>
<tr>
<td>7.6</td>
<td>CONCLUDING REMARKS</td>
<td>313</td>
</tr>
<tr>
<td>8</td>
<td>CONCLUDING REMARKS AND SCOPE OF FUTURE WORK</td>
<td>334-336</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>337-350</td>
</tr>
<tr>
<td></td>
<td>BIO-DATA</td>
<td>351.</td>
</tr>
</tbody>
</table>