

EXPERIMENTAL INVESTIGATION AND CFD MODELLING  
OF MULTI-SIZED PARTICULATE SLURRY FLOW THROUGH  
PIPELINE

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OF MULTI-SIZED PARTICULATE SLURRY FLOW THROUGH  
PIPELINE

by

**ASSEFA KEBEDE**

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of **Doctor of Philosophy**

to the



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Dedicated

to

my beloved mother

Ms. Tadelech Jofe

## Certificate

This is to certify that the thesis entitled “**Experimental Investigation and CFD Modelling of Multi-Sized Particulate Slurry Flow through Pipeline**” being submitted by **Mr. Assefa Kebede** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** in civil engineering is a bonafide record of research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy. The research reports and results presented 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.

(**Deo Raj Kaushal**)

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Assefa Kebede

August, 2017

“ሥራህን ለአግዚአብሔር አደራ ስጥ፥ አሳብህም ትጸናለች።”

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## Abstract

The presence of wide distribution of fine and coarse particles in the slurry transporting through pipeline critically influence the flow behaviours such as pressure drop. In the past decades, a number of techniques capable of reducing pressure drop either by altering the rheological properties or by reducing the impact of adverse flow properties of the slurries, have been investigated. Determining these complex flow behaviours through experiments become very difficult and expensive. Hence, numerous mathematical expressions of varying complexity and form have been proposed in the past. Many of these equations available in literature are developed based on limited data and their applicability is also limited. For these reasons, computational fluid dynamics (CFD) based simulations offers a relatively easy alternative and is becoming increasingly attractive due to recent advances in numerical models. Based on these notions, the following works have been carried out.

In the first stage of present work, the effects of non-chemical additives on the rheological properties of coal ash slurries have been studied using advanced computerized rotational rheometer. Solid bottom ash (BA) was added in the fly ash (FA) slurry and solid FA was used as additive in the BA slurry at various solid concentrations and mixing proportions. The investigation showed the FA slurries with and without the addition of BA behave as Bingham plastic and substantial reduction in yield stress was observed up 30% additive. On the other hand, the BA slurries with and without the addition of FA behave as Newtonian fluids at all concentrations and additive proportions. Furthermore, the viscosity increases with increasing the concentrations as well as the proportion of FA.

Likewise, the influence of chemical agents, namely quick lime (QL), hydrated lime (HL), sodium hexametaphosphate (SHMP) and Acti-Gel, on the rheological behaviors of iron ore slurries at different solid concentrations and additives dosages have been

investigated. Moreover, based on the rheological data the impact of these chemical agents on the pressure drop along slurry pipeline were analyzed using numerical model. The investigation showed that the minimum shear stress and viscosity were obtained at 2% dosage of QL for 18.8% and the minimum flow behaviour index was obtained at 25.8% with 2% additive dosage. The addition of HL markedly increases all the rheological parameters. When SHMP is used, the minimum shear stress and viscosity were obtained at dosage of 1.5%, 2% and 2% for 50%, 55% and 60% respectively. Acti-Gel resulted higher values of yield stress and flow behaviour indices at all solid concentrations. It is also indicated that QL was more effective in reducing the friction factor than HL, SHMP and Acti-Gel. At high flow velocities and low dosages, SHMP yielded the minimum friction factors. But, the addition of Acti-Gel yielded larger results than the rest.

In the second stage of present work, a new empirical model has been developed for the viscosity of multi-sized Bingham plastic as a function of solid volume fraction, the maximum solid volume fraction, intrinsic viscosity, median particle diameter, and coefficient of uniformity using optimization and nonlinear least square curve fitting techniques. A bench scale test was carried out to obtain the rheological properties of the slurries at high solid concentrations. Additional data have also been collected from open literature. The predicted viscosity based on the proposed model was compared with these data and found to be much better than the previously developed models over the entire range of volume fraction.

Similarly a new approach for predicting the pressure drop multi-sized slurry flow along slurry pipeline has been proposed. Prior to this, the accuracy and applicability of the existing explicit friction factor correlations developed for smooth pipes have been examined. Nine models developed for different flow regimes were chosen and the comparisons of the selected equations with the experimental data were expressed through MARE, RMSE,  $\Theta$ , S, AIC and MSC. The analyses showed that the Wilson-Thomas

(1985) and Morrison (2013) models are the best fit models for the Reynolds number up to 40000 but beyond this value the Morrison model showed better predictions. Hence, this model can be used as an alternative to the Moody chart and other implicit formulae developed for smooth pipes. Furthermore, new simplified approaches were adopted to improve the Wasp model for predicting the pressure drops of multi-sized slurry flowing through pipeline. The two implemented approaches are the physico-rheological approach that takes into account the particle size distribution as well as slurry viscosity and the multiphase flow modelling approach that considers the different flow regimes. Extensive experiments were carried out to measure the physical properties, rheological behaviours and pressure drops at various solid concentrations. Moreover, additional data were collected from open literature. The predicted pressure drops obtained by the proposed approach were compared with model of Williamson and Kaushal & Tomita. It is concluded that the current approach provides an improved results over previously available models and is also broader in scope of considering wider range of solid concentrations.

In the last stage of present work, the performance of Eulerian multiphase model coupled with  $k-\epsilon$  turbulence closures along with its model alternatives based on the types of secondary phase, near wall treatment and pipe roughness were evaluated using ANSYS FLUENT 14.0. The simulated results were compared with the experimental data and with numerical equations chosen from open literature. If CPU memory storage and computational time are not an issue, granular realizable model with standard wall function is capable of accurately simulating the slurry flow through pipeline. Finally, based on the above findings, the CFD simulation of iron ore slurry flowing through horizontal pipeline at various solid concentrations and flow velocities have been carried out. The CFD predicted pressure drops were compared with own measured data and showed maximum RMSE of 17.36% at all concentrations and flow velocities. Hence, it can be concluded that the CFD predicted results were in good agreement with measured data.

## सार

पाइपलाइन के माध्यम से ले जाने वाले गारामें ठीक और मोटे कणों के व्यापक वितरण की उपस्थिति दबाव बूंद के रूप में प्रवाह व्यवहार को गंभीर रूप से प्रभावित करते हैं। पिछले दशकों में, रियालिक गुणों को बदलने या घोलों के प्रतिकूल प्रवाह गुणों के प्रभाव को कम करके दबाव ड्रॉप को कम करने में सक्षम कई तकनीकों की जांच की गई है। प्रयोगों के माध्यम से इन जटिल प्रवाह व्यवहारों को निर्धारित करना बहुत ही कठिन और महंगा है। अतः अतीत में जटिलता और रूप में भिन्नता के कई गणितीय अभिव्यक्तियां प्रस्तावित की गई हैं। साहित्य में उपलब्ध इन समीकरणों में से कई सीमित डेटा के आधार पर विकसित किए गए हैं और उनकी प्रयोज्यता भी सीमित है। इन कारणों से, कम्प्यूटेशनल द्रव डायनेमिक्स (सीएफडी) आधारित सिमुलेशन अपेक्षाकृत आसान विकल्प प्रदान करता है और संख्यात्मक मॉडल में हालिया प्रगति के कारण तेजी से आकर्षक होता जा रहा है। इन धारणाओं के आधार पर, निम्न कार्य किए गए हैं।

वर्तमान काम के पहले चरण में, कोयले की राख के गाराके रियोलॉजिकल गुणों पर गैर-रासायनिक कई योजकके प्रभाव का अध्ययन किया गया है उन्नत कंप्यूटरीकृत घूर्णी रियो मीटरका उपयोग कर। ठोस तल राख (बीए) फ्लाइ एश (एफए) के घोल में जोड़ा गया था और ठोस एफए को विभिन्न ठोस सांद्रता और मिश्रित अनुपातों पर बीए स्लरी में जोड़ के रूप में इस्तेमाल किया गया था। जांच ने बीए के अलावा बिना और इसके अलावा एफए घोलदिखाया बिंघमप्लास्टिक के रूप में व्यवहार और उपज तनाव में काफी कमी 30% योजक देखा गया था। दूसरी तरफ, एफए के अलावा बिना और बिना बीए स्लीरिज़स सभी सांद्रता और संयोजी अनुपातों पर न्यूटनियन तरल पदार्थ के रूप में व्यवहार करते हैं। इसके अलावा, सांद्रता और साथ ही एफए के अनुपात में वृद्धि के साथ चिपचिपापन बढ़ जाता है।

इसी तरह, विभिन्न ठोस सांद्रता और कई योजक 'खुराक पर रासायनिक एजेंटों, अर्थात् जल्दी चूने (क्यूएल), हाइड्रेटेड चूने (एचएल), सोडियम हेक्समेटाफोस्फेट (एसएमएमपी) और एक्टि-जेल, के रियोलॉजिकल व्यवहार पर प्रभाव की जांच की गई है। इसके अलावा, रियोलॉजिकल आंकड़ों के आधार पर इन रासायनिक एजेंटों के प्रभाव को स्लरी पाइपलाइन के साथ दबाव ड्रॉप पर विश्लेषण किया गया था जो कि संख्यात्मक मॉडल का उपयोग किया गया था। जांच से पता चला कि न्यूनतम कतरनी तनाव और

चिपचिपापन 18.8% के लिए क्यूएल के 2% खुराक पर प्राप्त किया गया था और न्यूनतम प्रवाह व्यवहार सूचकांक 2% योजक खुराक के साथ 25.8% पर प्राप्त किया गया था। एचएल के वृद्धि पर सभी रियोलिक पैरामीटर बढ़ते हैं। जब एसएचएमपीका प्रयोग किया जाता है, तब न्यूनतम कतरनी तनाव और चिपचिपापन क्रमशः 1.5%, 2% और 2% के लिए 50%, 55% और 60% की खुराक पर प्राप्त किया गया था। एक्टि-जेल ने उपज तनाव के उच्च मूल्य और सभी ठोस सांद्रताओं पर प्रवाह व्यवहार सूचकांकों का परिणाम दिया। यह भी पाया गया है कि क्यूएल एचएल, एसएचएमपी और एक्टि-जेल से घर्षण कारक को कम करने में अधिक प्रभावी था। उच्च प्रवाह वेग और कम मात्रा पर, एसएचएमपी ने न्यूनतम घर्षण कारक उत्पन्न किया। लेकिन, बाकी के अलावा एक्टि-जेल के जोड़ पर बड़े परिणाम सामने आए।

वर्तमान कार्य के दूसरे चरण में, बहुआयामी बिंगहैम प्लास्टिक की चिपचिपाहट के लिए ठोस मात्रा अंश, अधिकतम ठोस मात्रा अंश, आंतरिक चिपचिपाहट, मध्यक कण व्यास, और अनुकूलन का उपयोग करके एकरूपता के गुणांक के रूप में एक नया अनुभवजन्य मॉडल विकसित किया गया है। और गैररेखा कम से कम वर्ग वक्र फिटिंग तकनीक उच्च ठोस सांद्रता पर घोलके रियोलॉजिकलगुण प्राप्त करने के लिए एक बेंच पैमाने परीक्षण किया गया था। साहित्य से अतिरिक्त डेटा भी एकत्र किया गया है। प्रस्तावित मॉडल के आधार पर अनुमानित चिपचिपापन की तुलना इन आंकड़ों के साथ की गई और मात्रा के अंश की पूरी रेंज से पहले विकसित मॉडल की तुलना में बेहतर पाया गया।

इसी तरह, स्लरी पाइपलाइन के साथ दबाव ड्रॉप बहुआयामी घोल प्रवाह की पूर्वानुमान के लिए एक नया दृष्टिकोण प्रस्तावित किया गया है। इससे पहले, चिकनी पाइप के लिए विकसित मौजूदा स्पष्ट घर्षण कारक संबंधों की सटीकता और प्रयोज्यता की जांच की गई है। विभिन्न प्रवाह व्यवस्थाओं के लिए विकसित किए गए नौ मॉडल को चुना गया और प्रयोगात्मक आंकड़ों के साथ चयनित समीकरणों की तुलना मैर, आरएमएसई, ए, एस, एआईसी और एमएससी के माध्यम से व्यक्त की गई। विश्लेषणों से पता चला है कि विल्सन-थॉमस (1985) और मॉरिसन (2013) मॉडल रेनॉल्ड्स संख्या 40000 तक के लिए सबसे अच्छे मॉडल हैं लेकिन इस मूल्य से परे मॉरिसन मॉडल ने बेहतर पूर्वानुमानको दिखाया। इसलिए, इस मॉडल को मूडी चार्ट के वैकल्पिक और चिकनी पाइप के लिए विकसित अन्य अंतर्निहित फ़ार्मुलों के रूप में इस्तेमाल

किया जा सकता है। इसके अलावा, पाइपलाइन के माध्यम से बहने वाले बहु आकार के मलिनू के दबाव के बूंदों की पूर्वानुमानके लिए वाश मॉडल को सुधारने के लिए नए सरल दृष्टिकोण अपनाए गए। दो कार्यान्वित दृष्टिकोण भौतिक-रूहोलॉजिकल दृष्टिकोण हैं जो कण आकार के वितरण को ध्यान में रखते हैं साथ ही स्लरी स्कीसीटी और मल्टीफेस फ्लो मॉडलिंग दृष्टिकोण जो कि विभिन्न प्रवाह व्यवस्थाओं को समझता है। विभिन्न ठोस सांद्रताओं पर भौतिक गुणों, राइजिकल व्यवहार और दबाव के बूंदों को मापने के लिए व्यापक प्रयोग किए गए। इसके अलावा, साहित्य से अतिरिक्त डेटा एकत्र किया गया। प्रस्तावित दृष्टिकोण से प्राप्त होने वाली अनुमानित दबाव की तुलना विलियमसन और कौशल और तोमिता के मॉडल के साथ की गई थी। यह निष्कर्ष निकाला है कि वर्तमान दृष्टिकोण ठोस सांद्रता के व्यापक रेंज में पहले उपलब्ध मॉडल के मुकाबले एक बेहतर परिणाम प्रदान करता है।

वर्तमान कार्य के अंतिम चरण में, एउलरियन मल्टीफेस मॉडल के प्रदर्शन को के- $\epsilon$ तंतुओं के साथ मिलकर इसके मॉडल विकल्प के साथ-साथ द्वितीयक चरण के प्रकार, दीवार के उपचार और पाइप खुरदरापन के आधार पर एएनएसआईएस फ्लुएंटे 14.0 का उपयोग करके मूल्यांकन किया गया। सिम्युलेटेड परिणाम की प्रयोगात्मक डेटा के साथ तुलना की गई थी और साहित्य से चुना गया संख्यात्मक समीकरणों के साथ। यदि सी पी यूस्मृति भंडारण और कम्प्यूटेशनल समय कोई समस्या नहीं है, तो मानक दीवार फ़ंक्शन के साथ दानेदार प्राप्य मॉडल पाइप लाइन के माध्यम से घोल प्रवाह का सटीक रूप से अनुकरण करने में सक्षम है। अंत में, उपरोक्त निष्कर्षों के आधार पर, विभिन्न सांद्रता और प्रवाह वेगों पर क्षैतिज पाइप लाइन के माध्यम से बहने वाले लौह अयस्क घोल का सीएफडी सिमुलेशन किया गया है। सीएफडी ने अनुमान लगाया है कि दबाव के बूंदों को स्वयं के आंकड़ों के साथ तुलना की जाती है और सभी सांद्रता और प्रवाह वेग पर अधिकतम 17.36% के आरएमएसई दिखाया गया है। इसलिए, यह निष्कर्ष निकाला जा सकता है कि सीएफडी ने अनुमानित आंकड़े मापा आंकड़ों के साथ अच्छे समझौते में थे।

## Table of Contents

<b>Certificate</b> .....	<b>i</b>
<b>Acknowledgement</b> .....	<b>iii</b>
<b>Abstract</b> .....	<b>i</b>
<b>Lists of figures</b> .....	<b>xv</b>
<b>Lists of tables</b> .....	<b>xix</b>
<b>Nomenclatures</b> .....	<b>xxi</b>
<b>Chapter 1</b>	
<b>Introduction</b> .....	<b>1</b>
1.1. Basics of Slurry Transportation Systems .....	1
1.2. Flow Patterns and Parameters Describing the Flow of Slurries.....	2
1.3. Modelling the Flow Behaviours of Highly Concentrated Slurries.....	3
1.4. Objectives of the Thesis .....	5
1.5. Scopes of the Study .....	6
1.6. Thesis Outlines.....	7
<b>Chapter 2</b>	
<b>Literature Review</b> .....	<b>11</b>
2.1. Slurry Flow Regimes in Pipeline.....	11
2.2. Types of Fluid Flow in Pipe .....	15
2.3. Settling and Critical Flow Velocity in Slurry Pipeline .....	16
2.3.1. Settling velocity .....	16
2.3.2. Critical (deposition) flow velocity.....	19
2.4. Rheology, Flow Behaviours, and Constitutive Equations .....	20
2.4.1. Rheology and flow behaviours of slurry .....	20
2.4.2. Factors affecting the rheological behaviour of the slurry.....	21
2.4.3. Rheological mathematical models.....	23
2.5. Equations of Flow Behaviours of Slurry in Pipelines.....	24
2.5.1. Models to predict pressure drop for slurry flows in horizontal pipelines .....	24
2.5.2. Models for solid concentration distributions in slurry pipelines.....	34

2.5.3. Equations for velocity profiles of slurry flow in pipelines .....	36
2.6. CFD Modelling of the Solid-Liquid Slurry Flow in Horizontal Pipelines.....	39
2.6.1. Steps in performing CFD analysis .....	40
2.6.2. Approaches to multiphase modeling .....	42
2.6.3. The Eulerian multiphase model.....	44
2.6.4. Modelling turbulence.....	51
2.6.5. k- $\epsilon$ model .....	53
2.6.6. Near wall treatment for turbulent flows .....	57
<b>Chapter 3</b>	
<b>Experimental Set Up and Measurements .....</b>	<b>63</b>
3.1. Uncertainties and Error Minimization Techniques .....	63
3.2. Materials and Instruments Used .....	64
3.3. Measuring Techniques Implimented in the Study .....	65
3.3.1. Particle size distribution (PSD).....	65
3.3.2. Specific gravity .....	69
3.3.3. Maximum static settled concentration.....	70
3.3.4. pH value .....	70
3.3.5. Rotational Rheometer .....	71
<b>Chapter 4</b>	
<b>The Effects of Non-Chemical Additives on the Rheological Properties of Coal Ash Slurries .....</b>	<b>75</b>
4.1. Introduction .....	75
4.2. Specific Objectives of the Study .....	79
4.3. Experimental Setup and Measurements .....	79
4.4. Test Materials and Range of Parameters .....	80
4.4.1. Test materials .....	80
4.4.2. Range of parameters .....	80
4.5. Results and Discussions .....	80

4.5.1. Physical properties of the samples.....	80
4.5.2. The effects of additions of BA on the FA slurries.....	83
4.5.3. The effects of additions of FA on BA slurries.....	90
4.5.4. A correlation to estimate the relative viscosity of BA slurry.....	95
4.6. Concluding Remarks.....	96
<b>Chapter 5</b>	
<b>The Influence of Chemical Agents on the Rheological Properties of Iron Ore Slurry and Impacts on Pressure Drops .....</b>	<b>97</b>
5.1. Introduction .....	97
5.2. Specific Objectives of the Study .....	100
5.3. Test Materials and Sample preparations.....	100
5.3.1. Test materials.....	100
5.3.2. Range of parameters .....	101
5.3.3. Samples preparation.....	101
5.4. Results and Discussions.....	102
5.5.1. The physical properties .....	102
5.5.2. Slurry rheological properties and model representation.....	104
5.5.3. Effects of chemical additives on the rheological behaviours of the slurry ..	106
5.5.4. Impacts of chemical agents on the pressure drops along slurry pipeline ....	120
5.6. Concluding Remarks.....	130
<b>Chapter 6</b>	
<b>A New Model for the Viscosity of Multi-Sized Particulate Bingham Slurry .....</b>	<b>131</b>
6.1. Introduction .....	131
6.2. Specific Objectives of the Study .....	134
6.3. Measurement Set Up.....	134
6.4. Experimentally Measured and Collected Data .....	135
6.4.1. Physical properties of the study samples .....	135
6.4.2. Rheological properties of the slurry .....	135
6.4.3. Computation of maximum packing concentration and intrinsic viscosity ..	141

6.5. Model Theory and Formulation.....	145
6.6. Optimization Based Model Coefficients Determination .....	148
6.7. Models Comparisons.....	150
6.8. Concluding Remarks.....	153
<b>Chapter 7</b>	
<b>Predictive Models for the Pressure Drop of Multi-Sized Particulate Slurry Flow through pipeline.....</b>	<b>155</b>
7.1. A Comparative Study on Friction Factors Correlations for Smooth Horizontal Slurry Pipelines .....	155
7.1.1. Introduction.....	155
7.1.2. Specific objectives of the study.....	156
7.1.3. The existing friction factors correlations.....	156
7.1.4. Statistical analysis and models computations .....	163
7.1.5. Evaluation of the selected friction factor correlations .....	165
7.1.6. Concluding remarks .....	167
7.2. A Simplified Approach for Wasp Model to Predict Pressure Drop along Slurry Pipeline .....	169
7.2.1. Introduction.....	169
7.2.2. Specific objectives of the study.....	171
7.2.3. Description of the existing models.....	171
7.2.4. The new simplified proposed approach .....	172
7.2.5. Measured and collected experimental data .....	175
7.2.6. Comparisons of the proposed model with previously existing models.....	177
7.2.7. Concluding remarks .....	189
<b>Chapter 8</b>	
<b>Performance Evaluation of the Eulerian model coupled with Different Turbulence Closures in the CFD Modelling of Slurry Flow through Pipeline.....</b>	<b>191</b>
8.1. Introduction .....	191
8.2. Specific Objectives of the Study .....	194

8.3. Mathematical Models .....	194
8.3.1. The governing equations .....	194
8.3.2. k- $\epsilon$ turbulent models .....	197
8.3.3. Wall boundary conditions .....	199
8.3.4. Transport equation for granular temperature .....	201
8.4. Numerical Computations .....	202
8.4.1. Properties of test materials .....	202
8.4.2. Geometrical construction and mesh independency test .....	202
8.4.3. Boundary conditions .....	203
8.4.4. Wall functions.....	204
8.4.5. Solution strategy and convergence.....	204
8.4.6. Entrance length .....	205
8.5. Modelling Results and Discussions.....	205
8.5.1. Pressure drops.....	205
8.5.2. Solid concentration distributions.....	209
8.5.3. Vertical velocity profiles.....	216
8.5.4. Computational time.....	221
8.6. Model Options Comparisons.....	222
8.7. Concluding Remarks.....	226
<b>Chapter 9</b>	
<b>CFD Modelling of Multi-sized Iron ore Slurry Flowing through Horizontal Pipeline .....</b>	<b>229</b>
9.1. Introduction .....	229
9.2. Properties of Test Materials .....	229
9.3. Numerical Computations.....	230
9.3.1. Geometrical construction and mesh independency test.....	230
9.3.2. Boundary conditions .....	231
9.3.3. Solution strategy and convergence.....	232

9.4. CFD Modelling Results and Discussions .....	232
9.4.1. Pressure drop .....	232
9.4.2. Solid concentration distribution across the pipe cross-section .....	234
9.4.3. Velocity profiles across the pipe cross-section .....	235
9.4.4. Turbulent viscosity ( $\mu_t$ ) .....	239
9.5. Concluding Remarks.....	242
<b>Chapter 10</b>	
<b>Summary and Conclusions .....</b>	<b>243</b>
<b>References.....</b>	<b>245</b>
<b>Research Publications .....</b>	<b>273</b>
International Journals .....	273
Conference Papers.....	274
<b>Brief biodata.....</b>	<b>275</b>

## Lists of figures

<b>Fig. 2 1.</b> Flow regimes in terms of particle size vs flow velocity.....	13
<b>Fig. 2 2.</b> Flow regimes in terms of flow velocity vs pressure drop in a log-log curve.....	14
<b>Fig. 2 3.</b> Schematic presentation of flow patterns and concentration distributions .....	14
<b>Fig. 2 4.</b> Horizontal components of velocity for laminar and turbulent flows at point P.....	16
<b>Fig. 2 5.</b> Velocity profile with the boundary layers for laminar and turbulent flows.....	16
<b>Fig. 2 6.</b> Regions of boundary layers in turbulent flow .....	39
<b>Fig. 3. 1.</b> Rotational rheometer with its components .....	73
<b>Fig. 4. 1.</b> Particle size distributions of FA and FA+BA mixtures .....	81
<b>Fig. 4. 2.</b> Particle size distributions of BA and BA+FA mixtures .....	82
<b>Fig. 4. 3.</b> Rheology of FA slurry at various solid concentrations.....	84
<b>Fig. 4. 4.</b> Rheogram of FA & mixture of FA – BA at 60% concentration by weight.....	85
<b>Fig. 4. 5.</b> Rheogram of FA & mixture of FA – BA at 62% concentration by weight.....	86
<b>Fig. 4. 6.</b> Rheogram of FA & mixture of FA – BA at 65% concentration by weight.....	87
<b>Fig. 4. 7.</b> Rheogram of FA slurries with the addition of 40 % of BA by weight.....	88
<b>Fig. 4. 8.</b> Yield stress and shear infinite shear viscosity of FA without and with the addition of BA at various concentrations.....	89
<b>Fig. 4. 9.</b> The rheogram of BA slurry without and with addition of FA.....	92
<b>Fig. 4. 10.</b> Shear stress of BA slurries without and with addition of FA .....	94
<b>Fig. 5. 1.</b> Particle size distribution of the iron ore sample .....	102
<b>Fig. 5. 2.</b> pH values of the iron ore slurries at different solid concentration and additive amount.....	103
<b>Fig. 5. 3.</b> Selection of best fit model to the measured data of QL at different volumetric solid concentrations and chemical proportions.....	106
<b>Fig. 5. 4.</b> Rheogram of iron ore slurries at QL dosages of 0 to 2% and Cw of 50%.....	110
<b>Fig. 5. 5.</b> Rheogram of iron ore slurries at QL dosages of 0 to 2% and Cw of 55%.....	111
<b>Fig. 5. 6.</b> Rheogram of iron ore slurries at QL dosages of 0 to 2% and Cw 60%.....	112
<b>Fig. 5. 7.</b> Rheogram of iron ore slurries at HL dosages of 0 to 2% and Cw 50%.....	113

<b>Fig. 5. 8.</b>	Rheogram of iron ore slurries at HL dosages of 0 to 2% and Cw 55% .....	114
<b>Fig. 5. 9.</b>	Rheogram of iron ore slurries at HL dosages of 0 to 2% and Cw 60% .....	115
<b>Fig. 5. 10.</b>	Rheogram of iron ore slurries at SHMP dosages of 0 to 2% and Cw 50% .....	116
<b>Fig. 5. 11.</b>	Rheogram of iron ore slurries at SHMP dosages of 0 to 2% and Cw 55% .....	117
<b>Fig. 5. 12.</b>	Rheogram of iron ore slurries at SHMP dosages of 0 to 2% and Cw 60% .....	118
<b>Fig. 5. 13.</b>	Rheogram of iron ore slurries at Acti-Gel dosages of 0 to 2% and Cw 50% .....	119
<b>Fig. 5. 14.</b>	Rheogram of iron ore slurries at Acti-Gel dosages of 0 to 2% and Cw of 55% .....	119
<b>Fig. 5. 15.</b>	Rheogram of iron ore slurries at Acti-Gel dosages of 0 to 0.2% and Cw of 60% ..	120
<b>Fig. 5. 16.</b>	Friction factors at Cw = 50% and QL dosages of 0 - 2% .....	122
<b>Fig. 5. 17.</b>	Friction factors at Cw = 55% and QL dosages of 0 - 2%.....	123
<b>Fig. 5. 18.</b>	Friction factors at Cw = 60% and QL dosages of 0 - 2%.....	123
<b>Fig. 5. 19.</b>	Friction factors at Cw = 50% and HL dosages of 0 - 2%.....	124
<b>Fig. 5. 20.</b>	Friction factors at Cw = 55% and HL dosages of 0 - 2%.....	124
<b>Fig. 5. 21.</b>	Friction factors at Cw = 60% and HL dosages of 0 - 2%.....	125
<b>Fig. 5. 22.</b>	Friction factors at Cw = 50% and SHMP dosages of 0 - 2%.....	125
<b>Fig. 5. 23.</b>	Friction factors at Cw = 55% and SHMP dosages of 0 - 2%.....	126
<b>Fig. 5. 24.</b>	Friction factors at Cw = 60% and SHMP dosages of 0 - 2%.....	126
<b>Fig. 5. 25.</b>	Friction factors at Cw = 50% and Acti-Gel dosages of 0 - 0.2%.....	127
<b>Fig. 5. 26.</b>	Friction factors at Cw = 55% and Acti-Gel dosages of 0 - 0.2%.....	127
<b>Fig. 5. 27.</b>	Friction factors at Cw = 60% and Acti-Gel dosages of 0 - 0.2%.....	128
<b>Fig. 5. 28.</b>	The normalized friction factors as a function of flow velocities for different chemical agents at the same solid concentration.....	129
<b>Fig. 6. 1.</b>	PSD of the experimental samples in semi-log curve .....	135
<b>Fig. 6. 2.</b>	The shear stress and apparent viscosity of the experimental samples of S-1 .....	137
<b>Fig. 6. 3.</b>	The shear stress and apparent viscosity of the experimental samples of S-2 .....	138
<b>Fig. 6. 4.</b>	The shear stress and apparent viscosity of the experimental samples of S-3 .....	139
<b>Fig. 6. 5.</b>	Effects of particle size parameter ( $Cu/d_{50}$ ) on the viscosity of the slurry.....	141
<b>Fig. 6. 6.</b>	Graphical evaluation of $\phi_m$ for S-1, S-2, and S-3 .....	143
<b>Fig. 6. 7.</b>	Graphical evaluation of $[\eta]$ for S-1, S-2, and S-3 .....	145

Fig. 6. 8. Comparison between various models and the experimental data of S-1.....	152
<b>Fig. 6. 10.</b> Comparison between the experimental data and the proposed model values .....	152
<b>Fig. 7. 1.</b> Comparison between experimental data and models predicted for friction factor in smooth pipe .....	164
<b>Fig. 7. 2.</b> Comparison of the relative error of Morrison (2013) equation with the remaining models as a function of $Re$ .....	167
<b>Fig. 7. 3.</b> Measured pressure drop of water and iron ore slurries as well as fly ash slurries ...	177
<b>Fig. 8. 1.</b> Predicted normalized concentration distributions across the pipe cross-section .....	211
<b>Fig. 8. 2.</b> Predicted normalized concentration distribution based on non-granular model and measured data .....	213
<b>Fig. 8. 3.</b> Predicted normalized concentration distribution based on granular model and measured data .....	215
<b>Fig. 8. 4.</b> Normalized velocity profile based on simulated and Eq. (8.38) results .....	218
<b>Fig. 8. 5.</b> Normalized velocity profile to the boundary layer thickness .....	220
<b>Fig. 8. 6.</b> Relative errors of the predicted pressure drop by each models options.....	224
<b>Fig. 8. 7.</b> Parity plots of modeled versus measured pressure drops .....	225
<b>Fig. 9. 1.</b> Meshed geometry with its inflation layers.....	231
<b>Fig. 9. 2.</b> CFD predicted pressure drops for measured iron ore slurry and measured data ....	233
<b>Fig. 9. 3.</b> Relative error of the CFD predicted pressure drop .....	233
<b>Fig. 9. 4.</b> Normalized solid concentration distribution across the slurry pipeline .....	235
<b>Fig. 9. 5.</b> The normalized velocity profile across slurry pipe cross-section at $C_{vf}$ of 5.66% ...	236
<b>Fig. 9. 6.</b> Normalized velocity profile across the slurry pipe cross-section at $C_{vf}$ of 13.45%..	237
<b>Fig. 9. 7.</b> Normalized velocity profile across slurry pipe cross-section at $C_{vf}$ of 34.27% .....	238
<b>Fig. 9. 8.</b> $\mu t$ at $C_{vf} = 34.27\%$ along the slurry pipeline at distance $X$ from the inlet .....	240
<b>Fig. 9. 9.</b> $\mu t$ at the maximum velocities of respective solid concentration .....	240
<b>Fig. 9. 10.</b> $\mu t$ at various velocities for $C_{vf} = 34.27\%$ .....	241
<b>Fig. 9. 11.</b> $\mu t$ at: (a) $C_{vf} = 5.66\%$ and $U_m = 4.98$ m/s; (b) $C_{vf} = 13.45\%$ and $U_m = 4.9$ m/s; (c) $C_{vf} = 34.27\%$ and $U_m = 2.72$ m/s.....	241

## Lists of tables

<b>Table 2. 1.</b> $CD$ as a function of particle Reynolds number ( $R_{ed}$ ).....	17
<b>Table 2. 2.</b> The values of $Z$ as a function of $Re_p$ .....	18
<b>Table 2. 3.</b> Correlations for critical velocity of slurry flowing in pipeline.....	20
<b>Table 2. 4.</b> Typical rheological models for fluids .....	24
<b>Table 4. 1.</b> Settling characteristics of coal ash slurries.....	82
<b>Table 4. 2.</b> pH values for coal ash at various slurry concentrations .....	82
<b>Table 4. 3.</b> $d_{50}$ for FA and mixture of FA and BA solid materials .....	82
<b>Table 4. 4.</b> $d_{50}$ for BA and mixture of BA and FA.....	83
<b>Table 4. 5.</b> Effects of adding BA on the rheology of FA slurry .....	90
<b>Table 4. 6.</b> Relative viscosity of the FA slurry at different concentrations.....	90
<b>Table 4. 7.</b> The shear and relative viscosity of BA and BA and FA mixtures.....	94
<b>Table 5. 1.</b> Rheological parameters data at various chemical additives of QL .....	108
<b>Table 5. 2.</b> Rheological parameters data at various chemical additives of HL .....	109
<b>Table 5. 3.</b> Rheological parameters data at various chemical additives of SHMP .....	109
<b>Table 5. 4.</b> Rheological parameters data at various chemical additives of Acti-Gel..	110
<b>Table 6. 1.</b> The relative viscosity of the sample data, S-1 to S-5.....	136
<b>Table 6. 2.</b> The relative viscosity of the sample data, S-6 to S-12.....	136
<b>Table 6. 3.</b> The computed values of $\phi_m$ and $[\eta]$ of the samples data.....	145
<b>Table 6. 4.</b> Equations suggested for the new model development .....	148
<b>Table 6. 5.</b> Estimated values of coefficients and uncertainties.....	149
<b>Table 6. 6.</b> Calculated values of statistical parameters for the selected models .....	151
<b>Table 7. 1.</b> The plastic viscosity of the sample slurries at various concentrations.....	176
<b>Table 7. 2.</b> Additional experimental data used in the study.....	177
<b>Table 7. 3.</b> RMSE (%) of the proposed and existing models for all samples data .....	180
<b>Table 8. 1.</b> The chosen models for granular properties in CFD FLUENT .....	196

<b>Table 8. 2.</b> Properties of materials used for this study .....	202
<b>Table 8. 3.</b> Grid independence test ( $U_m = 0.5\text{m/s}$ ; $C_{vf} = 0.3$ ; $d_{50} = 0.125\text{mm}$ ) .....	203
<b>Table 8. 4.</b> $\Delta P/L$ for non-granular $k-\epsilon$ with mixture turbulence model (NG-M).....	207
<b>Table 8. 5.</b> $\Delta P/L$ for non-granular $k-\epsilon$ with turbulence model per phases (NG-P)....	207
<b>Table 8. 6.</b> $\Delta P/L$ for granular $k-\epsilon$ with mixture turbulence model (G-M) .....	208
<b>Table 8. 7.</b> $\Delta P/L$ for granular $k-\epsilon$ with turbulence model per phases (G-P) .....	208
<b>Table 8. 8.</b> The computational time (hrs) taken to converge the iterations.....	221
<b>Table 8. 9.</b> Overall RMSE (%) values for the selected models options .....	222
<b>Table 9. 1.</b> Properties of materials used for this study .....	230

# Nomenclatures

## Greek letters

$\beta$	Dimensionless particle diffusivity (=1)
$\tau$	Shear stress at a given shear rate (Pa)
$\xi$	Dimensionless eddy diffusivity
$\tau_y$	Yield shear stress at zero shear rate (Pa)
$\varepsilon_s$	Particle diffusivity
$\tau_B$	Bingham yield stress (Pa)
$\rho_l$	Density of carrier fluid (kg/m <sup>3</sup> )
$\rho_m$	Slurry density (kg/m <sup>3</sup> )
$\rho_s$	Density of solid suspension (kg/m <sup>3</sup> )
$\eta_p$	Plastic viscosity (Pa. s)
$\eta_m$	Slurry viscosity (Pa. s)
$\eta_r$	Relative viscosity
$\eta$	Apparent viscosity (Pa.s)
$\eta_l$	Viscosity of a carrier fluid (Pa. s)
$\eta_{r,0}$	Relative viscosity at low shear rate
$\eta_s$	Viscosity of solid suspensions (Pa. s)
$\eta_\infty$	Infinite shear viscosity (Pa. s)
$\eta_{r,\infty}$	Relative viscosity at high shear rate
$\eta(t)$	Viscosity of water at test temperature (Pa. s)
$[\eta]$	Intrinsic viscosity
$\dot{\gamma}$	Shear rate (s <sup>-1</sup> )
$\phi$	Solid volume fraction
$\phi_m$	Maximum static solid volume fraction

## Lists of symbols

$C_D$	Drag coefficient
$C_f$	Fanning friction factor
$C_{vf}$	Efflux solid volume concentration
$C_v(y)$	Local solid volume concentration
$C_v'(y)$	Normalized volume solid concentration = $C_v(y)/C_{vf}$
$C_{vss}$	Volumetric static settled concentration
$C_{vj}$	Volumetric concentration of the $j^{\text{th}}$ size fraction
$C_{wf}$	Efflux solids concentration by weight (%)
$C_{wss}$	Static settled concentration by weight (%)
$d_{ch}$	Cut particle size ( $\mu\text{m}$ )
$d_j$	Mean diameter of the $j^{\text{th}}$ size fraction ( $\mu\text{m}$ )
$d_{ji}$	$i^{\text{th}}$ particle size in the $j^{\text{th}}$ parts of the PSD ( $\mu\text{m}$ )
$d_m$	Mean particle diameter ( $\mu\text{m}$ )
$d_{wmdf}$	Weighted mean diameter ( $\mu\text{m}$ )
$d_{50}$	Particle median diameter ( $\mu\text{m}$ )
$D$	Pipe diameter (m)
$\varepsilon/D$	Relative pipe roughness
$f$	Darcy-Weisbach friction factor
$f_{av, exp}$	Average friction factor of the experimental data
$f_{exp}$	Experiment friction factor
$f_L$	Friction factor for laminar flow
$f_{pred}$	Predicted friction factor
$f_T$	Friction factor for turbulent flow
$f'$	Normalized friction factor
$g$	Gravitational acceleration ( $\text{m/s}^2$ )

$G_b$	Generation of turbulent kinetic energy due to buoyancy
$G_k$	Generation of turbulent kinetic energy due to velocity gradients
$He$	Hedstrom number
$i_m$	Mixture head gradient
$i_v$	Pressure gradient due to vehicle
$i_w$	Clear water head gradient
$k$	von Karman constant (= 0.4)
$K$	Flow consistency index (Pa.s <sup>n</sup> )
$L$	Pipe length (m)
$n$	Flow behaviour index
$P_{ji}$	$i^{\text{th}}$ percent fraction in $j^{\text{th}}$ parts of the PSD (%)
$P_{het,j}$	Total percent fraction of solids in $j^{\text{th}}$ parts of PSD (%)
$R$	Radius of the pipe
$Re$	Reynolds number
$Re_B$	Reynolds number for Bingham Plastic
$Re_d$	Particle Reynolds number
$Re_{dh}$	Reynolds number based on the pipe hydraulic diameter
$Re_m$	Slurry Reynolds number
$Re_{mod}$	Modified Reynolds number
$Re_{sp}$	Settling particle Reynolds number
$S$	Modulus of the mean rate-of-strain tensor
$S_s$	Specific gravity of solid particles
$S_w$	Specific gravity of water at test temperature
$U'_m(y)$	Normalized velocity profile = $U_m(y)/U_m$
$U_m(y)$	Local flow velocity at the vertical position $y$
$U_m$	Inflow velocity (m/s)

$U^*$	Friction velocity
$V_{lm}$	Volume of water in settling slurry = $V_I - (V_{mo} - V_{mi})$ , (ml)
$V_{mi}$	Volume of settled slurry at any given time (ml)
$V_{mo}$	Initial volume of slurry (ml)
$V_t$	Unhindered settling velocity (m/s)
$V_I$	Volume of water taken (ml)
$w_{jo}$	Unhindered settling velocity of mean diameter of the $j^{\text{th}}$ size fraction (m/s)
$w_s$	Weight of solid particles (gm)
$\Delta P/L$	Pressure drop per meter length (Pa/m)

## Abbreviations

AIC	Akaike Information Criterion
ASM	Algebraic Slip Mixture
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
BA	Bottom Ash
HL	Hydrated Lime
FA	Fly Ash
IPSA	Inter-Phase Slip Algorithm
LES	Large Eddy Simulation
MARE	Mean Absolute Relative Error
PRE	Percent Relative Error
PSD	Particle Size Distribution
QL	Quick Lime
RANS	Reynolds Averaged Navier Stokes
RMSE	Root Mean Square Error
RNG	Re-Normalized Group
RSM	Reynolds Stress Model
SHMP	Sodium hexametaphosphate
SST	Shear Stress Transport