

**EXPERIMENTAL INVESTIGATIONS AND
CFD MODELING OF HYDRAULIC
CONVEYING THROUGH PIPELINE**

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**EXPERIMENTAL INVESTIGATIONS AND
CFD MODELING OF HYDRAULIC
CONVEYING THROUGH PIPELINE**

By

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CERTIFICATE

This is to certify that the thesis “**EXPERIMENTAL INVESTIGATIONS AND CFD MODELING OF HYDRAULIC CONVEYING THROUGH PIPELINE**” being submitted by **Mr. NAVNEET KUMAR** to the **Indian Institute of Technology Delhi, New Delhi (India)** for the award of the degree of Doctor of Philosophy in Civil Engineering Department is a bonafide research work carried out by him under my supervision and guidance. The thesis in my opinion, has reached the standard fulfilling the requirements for the 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.



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ABSTRACT

Conveying of granular solids in slurry form through pipeline systems is widely applied in industries due to its several inherent advantages, such as, continuous delivery, flexible routing, ease in automation and long distance transport capability, etc. The present need of energy and water resources conservation, industrial requirement of transporting a large quantity of solids mass and improved understanding of the flow mechanism of low concentration solids (10-40% by weight) slurry (Verkerk 1985; Sive and Lazrus 1986; Kumar 1999; Kumar 2010; Kaushal et al., 2013) have given an impetus to the emergence of higher solids concentration (>40% by weight) slurry transport systems (Elliot 1970; Wilson 1982; Slatter 1996; Gillies et al., 2000; Kaushal et al., 2005; Kaushal and Kumar 2013) which adds a new dimension to the slurry transport arena. In recent years, enhanced capabilities of turbulent flow modeling tools have provided a basic framework for the analysis of slurry pipeline systems. A significant number of literatures on low concentration (10-40% by weight) slurry transport systems have reasonably explained the transport mechanism of solids but the phenomenon is not yet to be fully understood for conveying of higher concentration slurry owing to complex interactions among the constituent phases. Therefore, the present study attempts to investigate the behaviour of higher concentration slurry transport systems.

Advent of highly sophisticated computers with advanced numerical techniques involved in computational fluid dynamics (CFD) analysis made it possible to analyze the operation of higher concentration slurry transport systems using numerical simulations but the literature review clearly reveals that the application of CFD for higher concentration slurry transport systems is few. The present research work delves deep into

the transport mechanism of higher concentration slurries by conducting experiments and numerical simulations.

In fact, the present knowledge base of slurry pipeline design is still not complete, particularly for higher concentration slurries, since the designers of slurry transport systems yet rely on the data generated from pilot plant test facility. Additionally, a huge cost involved in setting up a new slurry pipeline system demands for the cost to be minimized. This essentially requires a sound design methodology to implement an optimization method for the same purpose. The literature review confirms that the optimum values of parameters for the design of the slurry pipeline systems are also not yet established. Sparse published data on the flow of higher concentration slurries across a pipeline bend further add to the difficulty level of the complex problem.

Considering a large number of higher solids concentration slurry pipelines operating across the world and their associated problems, the present study aims to generate an extensive experimental dataset from the pilot plant test facility and to carry out computational fluid dynamics (CFD) simulations for better understanding of the flow behaviour of higher solids concentration slurry through pipeline. The experimental investigations were performed using various types of granular media and different diameter pipes. Physical properties, namely, specific gravity, particle size distribution, ph-value, static settled concentration, and rheological characteristics of iron ore and coal ash slurries (fly ash and a blend of fly and bottom ash) at various concentrations (ranging from low to high) were experimentally obtained to establish a classification criterion for the slurries having different concentrations. It was observed that the solids concentration played a vital role in defining the classification criterion. The slurries of different materials at higher solids concentration were found to display a non-Newtonian Bingham plastic, behaviour, whereas, at low concentration they exhibit Newtonian character.

Further, the rheological parameters, the plastic viscosity and the yield stress were also found to increase monotonically with the both, the increasing solids concentration and the decreasing particle size. The physical and rheological properties so obtained were used as input parameters to determine the pressure drop and concentration profile of the slurries flowing through pipeline. Experimental data relating to the pressure drop characteristics for the flow of fly ash and iron ore slurries were obtained from the pilot plant test facility which had 50 and 105 mm diameter pipes to facilitate investigation of the changes in the flow characteristics of commercial slurries and to correlate the efflux concentration and flow velocity with the various design parameters. Solids concentration profile, however, was also measured for the iron ore slurry. Experimental data collected in the present study and also those published in literature were analysed in relation to the results obtained from the CFD simulations. FLUENT software was applied to determine the design parameters of slurry transport systems and single-phase flow simulation was conducted to lay a basic framework for the multiphase flow system. The CFD simulation results obtained for the flow of water were found to completely agree with the experimental data, whereas, a relatively inferior agreement was observed between the simulation results and the data pertaining to the flow of higher solids concentration slurries.

Experiments were also performed to understand the flow behaviour of fly ash slurries at higher solids concentration across 90° horizontal bend in pipeline. The pressure drop across the pipe bend was found to be a function of solids concentration, pipe diameter, flow velocity, bend radius and angle, and size and specific gravity of the solid particles. The secondary flow generated at the bend location was identified as a key factor to influence the pressure drop and solids' distribution patterns which eventually affects the material erosion characteristic at the bend, however, the bend erosion characteristic was not investigated in the present study. The observed data for pipe bend were also

compared with the CFD simulation results and the comparison showed a reasonable agreement between the two.

The present work concludes that the results obtained by the CFD analysis for conveying of higher concentration slurries can be used by the designers to design a slurry pipeline system which eventually eliminates the need of expensive, time consuming and laborious experiments to be performed on pilot plant test facility for the design of higher concentration slurry pipeline.

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NOMENCLATURE

$C(y')$	Volumetric concentration at dimensionless height 'y'
C_D	Drag Coefficient
C_L	Coefficient of lift force
$C_v(y), C(y)$	Volumetric concentration at height 'y'
C_v	Slurry concentration by volume
C_{vf}	Average efflux concentration by volume
C_{vm}	Coefficient of virtual mass force
C_w	Slurry concentration by weight
D	Pipe diameter
d	Mean diameter of solid particles
d_{50}	Median particle diameter, 50% by weight particles are larger than d_{50}
d_i	Mean particle diameter of i^{th} size fraction
D_s	Eddy viscosity for the solid phase
d_s	Particle diameter
$D_{t,sf}$	Binary turbulent diffusion coefficient
e_{ss}	Restitution coefficient
f	Fluid phase
g	Acceleration due to gravity
$G_{k,f}$	Production of the turbulent kinetic energy in the flow
$g_{o,s}$	Radial distribution function
H_e	Hedstrom Number
I_{2D}	Second invariant of the deviatoric strain rate tensor
k	Turbulent kinetic energy

k	Von Karman constant
k_f	Co-variance of the velocity of fluid phase ‘f’ and solid phase ‘s’
k_f	Turbulent kinetic energy of the liquid phase
k_s	Turbulent kinetic energy of the solid phase
K_s	Height of surface roughness
k_{sf}	Co-variance of the velocity of fluid phase ‘f’ and solid phase ‘s’
K_{sf}, K_{fs}	Interphasial momentum exchange coefficients
$k_{\Theta s}$	Diffusion coefficient
M	Measured value
M_{av}	Mean measured value
P_s	Solid pressure gradient or the inertial force due to particle interactions
R	Bend radius
r	Pipe radius
Re	Reynolds number
s	Solid phase
S	Simulated value
S_{av}	Mean simulated value
u	Tangential velocity, x-direction flow velocity
u^*, u_τ	Friction velocity
U^+	Dimensionless mean velocity
U_f	Phase-weighted velocity
V, V_m	Mixture velocity
V_0	Terminal settling velocity
V_f	Mean flow velocity
V_r	Local relative velocity between particle and surrounding fluid

$V_{r,s}$	Terminal velocity correlation for solid phase
y	Normal distance to the pipe wall
y'	y/D
y_m	Distance of the liquid surface from the bottom of the channel
Z	Parameter = $V_0/\beta k u_*$
μ	Dynamic viscosity of fluid
μ_m	Mixture viscosity
μ_w	Viscosity of water at test temperature
$\gamma_{\Theta s}$	Collisional dissipation energy
$\tau_{F,sf}$	First time scale
Π_{kf}	Influence of the solid phase on the liquid phase
$\mu_{s,kin}$	Kinetic viscosity
ρ	Mass density
μ_f	Shear viscosity of water
τ_f	Stress tensor for fluid
$\tau_{t,f}$	Stress tensor for fluid due to turbulence
\vec{u}_{sf}	Slip-velocity
λ_s	Bulk viscosity of the solids
φ_{fs}	Transfer of the kinetic energy
$\left \vec{V}_r \right $	Average value of the local relative velocity

Re_B	Bingham Reynolds Number
$\mu_{s,col}$	Collisional viscosity
$\nabla\alpha_s$	Concentration fluctuations
ρ_f	Density of liquid
ρ_m	Density of mixture or slurry
ρ_s	Density of solids
\vec{u}_{dr}	Drift velocity
$\tau_{t,sf}$	Eddy-particle interaction time
$\mu_{s,fr}$	Frictional viscosity of solids
Θ_s	Granular temperature
Θ_s	Granular temperature
\bar{I}	Identity tensor
ϕ	Internal friction angle
$\mu_{s,kin}$	Kinetic viscosity of solids
ε_m	Mass transfer coefficient for the particles
ρ_m	Mixture density
f_m	Modified friction factor
Re_{mod}	Modified Reynolds number
ε_p	Particle diffusivity
τ_s	Particulate relaxation time

\vec{U}_f	Phase-weighted velocity
ε_f	Rate of dissipation for liquid phase
η_{sf}	Ratio between two characteristic times
Re_s	Relative Reynolds no. between phases
Re_m	Reynolds number for slurry
$\tau_{t,f}$	Second character time of energetic turbulent eddies
$\tau_{t,sf}$	Second time scale
τ	Shear stress
μ_s	Shear viscosity of solids (kg/ms)
τ_f	Stress tensor for fluid
τ_s	Stress tensor for solid
$\mu_{t,f}$	Turbulent viscosity
\vec{v}_f	Velocity of fluid phase
\vec{v}_s	Velocity of solid phase
α_f	Volumetric concentration of fluid phase
α_s	Volumetric concentration of solid phase
τ_y	Yield stress
$v_{fz}(x, y)$	Z-component of fluid velocity
ε_s	Mass transfer coefficient for the particles

f, f_T	Friction factor for pipeline (Fanning factor)
σ_{sf}	Dispersion Prandtl number
\bar{u}_i	Mean velocity components of flow
u'	Fluctuating velocity
β	Ratio of mass transfer coefficient to momentum transfer coefficient
γ	Shear rate
ε_l	Momentum transfer coefficient or liquid diffusivity
ε_s	Mass transfer coefficient or particle diffusivity
η_p	Plastic viscosity
η_r	Relative viscosity
θ	Angle between the mean particle velocity and mean relative velocity
μ_l	Viscosity of liquid or carrier fluid
μ_m	Viscosity of slurry

LIST OF ABBREVIATIONS

ARE	Average Relative Error
CFD	Computational Fluid Dynamics
CV	Coefficient of Variation
DEM	Discrete Element Method
DNS	Direct Numerical Simulations
FVM	Finite Volume Method
LBM	Lattice- Boltzmann Method
LES	Large Eddy Simulation
ME	Maximum Error
PDE	Partial Differential Equations
PSD	Particle Size Distribution
RANS	Reynolds Averaged Navier Stokes Equations
RNG	Re-Normalization Group
RSM	Reynolds Stress Model
RSM	Reynolds Stress Transport Models
VOF	Volume of Fluid