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Analysis of friction mechanism and homogeneity of suspended load for high concentration fly ash & bottom ash mixture slurry using rheological and pipeline experimental data

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ABSTRACT

The particle–fluid and particle–particle interactions governing the flow of highly concentrated power plant ash slurries containing fine-grained and coarse-grained ash particles have been investigated. The friction mechanism and suspension of coarse bottom ash fractions conveyed in a finer fly ash slurry vehicle were analyzed using the rheological and pipeline experimental data in a solid concentration range of 62.5–67.5% by weight. The degree of homogeneity and possible heterogeneously distributed solid fraction for the mixture slurry along the vertical axis of the pipe were evaluated using the well known Ismail's equation. A nearly non-settling nature of the pseudo-homogeneous mixture slurry at high solid concentration under laminar pipe flow regime has been observed. It has been determined that this sort of response is mainly due to the presence of granular Coulombic and Bagnold forces.

1. Introduction

The flow pattern of industrial minerals, tailings and other waste slurries with a wide range of particle size distribution is quite complex. The pipeline transportation of these materials at higher solid concentration ($C_W > 50\%$ by weight) still remains an active area of research. The suspension mechanism and accurate prediction of pressure drop for such fine–coarse mixture slurry comprising a relatively higher percentage of fines with respect to coarse particles require a thorough investigation to achieve pipe line flow economics under laminar flow conditions. A few theoretical investigations on suspension of settled bed particles in the presence of shear flow at very low Reynolds number in the laminar flow regime with negligible inertial effects have been cited in literature [1,2]. Further, the accurate prediction of pressure drop for high concentration slurries has been also shown to be affected due to the presence of coarse particles during pipeline transport. The economics of pipeline transport using stabilized flow slurries favors lesser pressure gradient which indicates that the nature of the flow of such slurries is very much influenced by the manipulation of particle size distribution [3,4]. This fine–coarse mixture slurries show the ability to support the coarse particles even under static conditions and hence such slurries could be pumped with reduced pumping cost under laminar conditions. It has been cited in the literature that the addition of a small fraction of coarse bottom ash to fly ash slurry at high solid concentration results in substantial reduction of pressure drop under laminar flow conditions [5–7]. It was indicated by Thomas [8] that the static stability criterion of a coarse particle in fine slurry medium based on yield stress might not hold good under laminar flow conditions, when the carrier fluid is sheared by an external agency. There have been some recent studies on the settling behavior of coarse particles in non-Newtonian slurries under laminar regime [9,10]. It seems most of the work have been conceptualized more or less with the same approach by considering stratified load of moving particles as opposed to a stationary bed to address the issue.

The use of modern instrumentation techniques for the measurement of concentration gradient, velocity profile etc. during pipe flow of concentrated suspensions has their own limitations in terms of accuracy, high cost, velocity ranges, pipe sizes, turbidity under high slurry concentrations etc. Some experimental and numerical modeling work on the flow structure of concentrated slurry, homogeneity in particle distribution without settling, concentration profile and pressure gradient influenced by particle size, solid volume fraction, velocity etc. has been reported in the literature [11–13]. Due to the lack of understanding of particle–particle and particle–fluid interaction, the numerical solutions performed on the hydrodynamic models ended up with limited success. Further, most of these studies confine to feasibility assessment of high concentration slurry flow. But the theoretical understanding of suspension mechanism governing the flow field has not been fairly expressed. Although the existence of stratification of coarse particles in a non-Newtonian carrier fluid cannot be ignored, yet, it is believed that such flow mechanisms can be analyzed using non-Newtonian stratified flow concepts.

The thermal power stations in India produce more than 150 million tons of coal ash (fly ash and bottom ash) per year which includes around 20% of bottom ash. The conventional lean phase ash

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Nomenclature

B_a	Bagnold number
C/C_A	ratio of solid volume concentrations at 0.08*D* from pipe top and at the pipe center
C_V	volume concentration, %
C_{Vb}	maximum solid volume fraction of the solids in the granular bed
C_W	weight concentration of slurry, %
d	diameter of the particle, m
d_{av}	average particle sizes of the four broad size fractions, µm
d_{50}	median particle size, µm
d_L	largest particle diameter in the particle size distribution of the two ash samples
d_S	smallest particle diameter in the particle size distribution of the two ash samples
f	friction factor
f_S	function of the solid fraction ϕ as defined in Eq. 6
f_n	function of the solid fraction ϕ as defined in Eq. 7
F_{bp}	buoyant force on the particles, N
$F_{bp\text{-}B}$	buoyant force due to bottom ash particles, N
$F_{bp\text{-}F}$	buoyant force due to fly ash particles, N
F_{gp}	total body force at the sheared bed of the pipe section, N
F_{GP}	gravitational force on a spherical solid particle, N
$F_{gp\text{-}F}$	body forces due to fly ash particles, N
$F_{gp\text{-}B}$	body forces due to bottom ash particles, N
F_{NB}	Bagnold's normal force component, N
F_{NC}	normal component of granular Coulombic force, N
F_{SB}	Bagnold's frictional force component, N
F_{Wp}	submerged weight of the particle, N
g	acceleration due to gravity, m/s^2
H_S	thickness of sheared bed, m
k	von *Kármán* constant for the slurry
K	consistency coefficient, $Pa\cdot s^n$
K_B	proportional coefficient in Eq. (9) for solid shear stress and is equal to 0.013
L	pipe length, m
n	power law flow behavior index
$N_{e\text{-}b}$	number of bottom ash particles
$N_{e\text{-}f}$	number of fly ash particles present in the mixture slurry supporting bottom ash particle
ΔP	applied pressure gradient in the pipeline, Pa
R_{eP}	Reynolds number of the particle
S_S	specific gravity of solids
U^*	friction velocity, m/s
U_t	terminal settling velocity of solids, m/s
V	pipe flow velocity, m/s

Greek letters

β	ratio of mass transfer coefficient to momentum transfer coefficient
μ_e	effective viscosity, Pa·s
δ	average clearance between particle surfaces, m
$\varnothing$	volume fraction
Ψ	distribution modulus
$\varnothing_{bed}$	heterogeneously distributed solid volume fraction
$\varnothing_{max}$	limiting (packing) volume fraction of solids
$\dot{\gamma}$	shear rate, s^{-1}
λ	linear concentration of solids as given by Bagnold in Eq. (9)
ρ_m	slurry density, kg/m^3
ρ_s	density of solid particle, kg/m^3
σ_{SB}	normal component of the Bagnold's dispersive stress, Pa
σ_{SC}	inter-granular normal stress, Pa
τ	shear stress, Pa
τ_{LP}	viscous shear stress, Pa
τ_{NB}	Bagnold's normal stresses, Pa
τ_{SB}	Bagnold's shear stress, Pa
τ_{SC}	inter-granular shear stress, Pa
$\tan\theta$	Coulombic friction coefficient

slurry pipeline systems presently adopted by the thermal power plants consume more than 630 million cubic meters of water per annum and require more than 25,000 ha of land including agricultural and forest lands for the disposal of these wastes [14,15]. In this paper the experimental data of rheological and pipeline studies on fly ash–bottom ash mixture slurry at high solid concentrations have been used to analyze the friction mechanism and homogeneity of suspended load for the mixture slurry. By conceptualizing the mixture as pseudo-homogeneous slurry, the suspension mechanisms of coarse bottom ash particles conveyed in a finer fly ash slurry medium have been presented. The presence of granular Coulombic and Bagnold stresses predominantly influencing the non-settling nature of ash mixture slurry at high solid concentration under laminar pipe flow regime has been discussed. The suspension mechanism has been further quantified by evaluating the degree of homogeneity and possible heterogeneously distributed solid fraction of the mixture slurry along the vertical axis of the pipe by applying the well known Ismail's equation [16,17].

2. Materials and methods

The NALCO Captive Power Plant situated at Angul in the state of Odisha, India uses high ash content (35–40% ash) bituminous coal for combustion in their pulverized corner firing water tube type boilers. These boilers produce fly ash and bottom ash in the weight ratio of approximately 80:20 and the ash samples collected from the Plant were used for the studies. The material densities of the fly ash and bottom ash samples determined in the laboratory experiments were found to be 2123 and 2165 kg/m^3 respectively. The chemical composition of the bulk ash sample was carried out by a Philips PW2400 X-Ray Spectrophotometer and the composition of major elements was Al_2O_3: 31.48%, SiO_2: 60.82%, Fe_2O_3: 5% and others: 2.7%. Five representative fly ash samples collected from different zones of electrostatic precipitator hoppers were prepared and leveled as S1, S2, S3, S4 and S5. The particle size distribution (PSD) of these samples was carried out using a Malvern Particle Size Analyzer (MASTERSIZER 2000, VER. 5.22, Malvern Instruments Ltd., UK). The median particle sizes (d_{50}) of the samples were found to be as 9, 19, 26, 39 and 52 µm for S1, S2, S3, S4 and S5 respectively. The particle size distribution of the bottom ash samples was carried out in a sieve shaker. Initially, the bottom ash samples were sieved in a BSS 16 mesh (having aperture: 1000 µm i.e. 1 mm) and the oversize was found to be around 20% which was discarded since the particles were of irregular shape and size. Therefore, only below 1 mm size bottom ash samples were used for the study. The median diameter (d_{50}) for the bottom ash sample was found to be 206 µm. The fly ash and bottom ash were mixed in the weight ratio of 5:1. Hence the bottom ash fraction in the mixed sample was kept as 0.166. The particle size distribution for the five fly ash samples mixed with bottom ash fractions is presented in Fig. 1.

The rheological experiments for the two fly ash samples S2 and S3 with the addition of bottom ash were conducted using a HAAKE Rotational Viscometer (Model RV 30) and a sensor system MVIII was chosen for this purpose. About 100 ml of slurry was prepared by mixing fly ash and bottom ash in the weight ratio of 5:1 in distilled water medium to obtain the desired concentration. Prior to transferring the slurry in to the cup, it was stirred gently by a glass rod for a period