Numerical Investigation of Slurry Pressure Drop at Different Pipe Roughness in a Straight Pipe Using CFD

Tanuj Joshi¹ · Om Parkash¹ · Gopal Krishan²

Received: 30 October 2021 / Accepted: 9 January 2022 / Published online: 18 February 2022
 © The Author(s) 2022

Abstract

Slurry flow (water–glass beads) through a horizontal pipe of diameter, 0.0549 m and length, 3.8 m with two particle sizes, i.e., 125- and 440-micron, has been numerically modeled and investigated based on the kinetic theory of slurry transportation. The effect of particles interaction on the pipe flow characteristics such as velocity profile, wall shear stress, vector regime, granular pressure and temperature has been evaluated at different solid concentration and flow velocity range. It is well established that the pressure drop is the key parameter for the design of efficient slurry pipeline system, which is influenced by factors such as flow velocity, slurry viscosity, solid concentration, pipe material and pipe geometry. However, to best of our knowledge, the estimation of pressure drop at different pipe roughness height and a concentration range of 40–60% is not yet established. Therefore, in the present work, the numerical simulation is carried out for slurry flow through a horizontal pipeline at different roughness heights ($R_h = 10\text{--}50$ micron) and Prandtl numbers, i.e., 1.34, 2.14, 3.42 and 5.83. The kinetic parameters are calculated at a flow velocity (V_m) of $1\text{--}5\text{ ms}^{-1}$ and solid concentration (C_w) range of 40–60%. The results and procedure of the current simulation are validated against the available experimental results in the literature. The outcomes of the present work reveals that pressure drop increases with increase in pipe roughness height for the chosen velocity and solid concentration range. In addition, the larger particle is found to have more influence on the pressure, velocity, temperature distribution for the entire range of flow velocity and solid concentration. Furthermore, settling velocity and specific energy consumption are also predicted and discussed through the slurry pipeline. The findings show that the settling velocity of particle increases with increase in particle size at different Prandtl number. The energy efficiency for solid transportation through pipeline at different Prandtl numbers and particle size are also evaluated. Based on the results, it is concluded that specific energy efficiency varies with solid concentration and particle size, i.e., higher concentration and larger particle size demonstrates higher energy consumption. Furthermore, fluid at low Prandtl number exhibits higher energy consumptions. In order to design the efficient slurry pipeline system, it is recommended that the slurry must be transported at low velocity and high Prandtl number.

Keywords Glass beads · Settling velocity · Specific energy consumption · Granular pressure · Granular temperature · Prandtl number

List of Symbols

$\dot{m}_{pf}, \dot{m}_{fp}$	Discrete mass transformation
$\bar{\tau}_f$	Phase tensor of fluid phase
$\bar{\tau}_p$	Phase tensor of solid phase

✉ Gopal Krishan
 Gkri408@aucklanduni.ac.nz

¹ Department of Mechanical Engineering, Amity University
 Haryana, Gurugram 122413, India

² Department of Mechanical Engineering, The University of
 Auckland, Private Bag 92019, Auckland 1142, New Zealand

K_{pf}	Solid–fluid exchange coefficient
$g_{o,PP}$	Inter collision b/w solid particulates
K	Thermal conductivity of fluid
∇P	Static pressure gradient (Pa)
∇P_s	Solid pressure gradient (Pa)
C_{vf}	Solid concentration (by volume)
C_p	Specific heat
ν	Momentum diffusivity
$g_{o,ss}$	Radial distribution function
P^*	Granular pressure
e	Restitution coefficient
$k_{\Theta s} \nabla \Theta_s$	Diffusive flux of granular energy

ε/Dt	Relative roughness
C_w	Solid concentration (by weight)
V_m	Mean flow velocity (ms^{-1})
g	Acceleration due to gravity (ms^{-2})
F_L	Settling velocity factor
C_V	Solid concentration (by volume)
d_{50}	Particle diameter
V_L	Settling velocity
D	Diameter of pipe (m)
s	Specific gravity of solid particle
s_l	Specific gravity of fluid
$\Delta P/L$	Pressure gradient
P_r	Prandtl number
$g_0(\phi)$	Radial distribution factor (RDF)
$k_{\Theta s}$	Diffusion coefficient
f	Fluid phase
$(-P_s \bar{\bar{\tau}} + \bar{\bar{\tau}}_s) : \nabla \vec{v}_s$	Energy generation by the solid stress tensor

Greek Symbols

$\alpha_P \rho_P$	Discrete phase density
μ_l	Shear viscosity of liquid phase (Pa-s)
μ_s	Shear viscosity of solid phase (Pa-s)
α_s	Solid phase concentration
α_l	Liquid phase concentration
ρ_s	Particle density (kg/m^3)
$\mu_{p,col}$	Collisional viscosity
ϕ_{max}	Maximum solid volume fraction
ϕ_{fs}	Transfer of kinetic energy of random fluctuation
$\alpha_P \rho_P$	Discrete phase density
α	Thermal diffusivity
μ_m	Fluid viscosity
ρ	Mass density (kg/m^3)
λ_P	Bulk viscosity of solid particle
$\mu_{p,kin}$	Kinetic viscosity
$\mu_{p,fr}$	Frictional viscosity
$\gamma_{\Theta s}$	Collisional dissipation energy

1 Introduction

Slurry transportation is a conventional system to transport solid particles through pipeline by mixing the solid particles with any carrier fluid (generally water) [1]. Slurry transportation through pipeline has wide range of industrial applications like disposal of the ash in thermal plants and petrochemical industries, transportation of waste, coal,

mining minerals and crust minerals. Transportation of slurries through pipelines is a rapid and efficient method which reduces material wastage and carbon emission. It is extensively used due to no contamination, low maintenance cost, less power consumption, approximately negligible wastage highly efficiency compared to bulk transportation through trucks and locomotives. Additionally, minimum pollution and safety prospective are common factors which boosts the utilization of slurry transportation system [2]. Multiple piping combinations like horizontal, vertical, inclined and bend pipes are considered as per the convenience of transportation. Slurry transportation is largely influenced by the major/minor variation into viscosity, particle size, shape, density, concentration, pipeline shape, etc. Several researchers in the past have carried out the experimental investigation to calculate the pressure drop of slurry in horizontal pipelines [3–5]. Techniques like computational fluid dynamics (CFD) provide an ease to analyze these problems with less time and minimal cost. Computational fluid dynamics (CFD) simulation provides the pressure drop which leads to the information about the flow characteristics, ultimately helping designers to design the appropriate pipeline system [6]. In addition, CFD simulation can help in exploring the minute details related to slurry flow characteristics which are almost impossible to predict from the experiments.

In nineteenth century, Darcy [7] conducted the pressure drop experiments on different set of pipes with different roughness and introduced a new term of relative roughness. In addition, a relationship between flow and pipe roughness, diameter and slope was established. Afterward, Fanning [8] proposed that pressure drop is a function of surface roughness. Colebrook et al. [9] experimentally studied the effect of surface roughness and its effect on the pressure drop. The average pipe roughness values were ranging from 0.04318 to 0.254 mm. It was determined that there is an inverse relation between velocity and friction factor. At fully developed flow profile, the effect of friction factor remains constant for higher velocities. Moody [10] characterized Darcy friction factor as a function of Reynolds number and relative roughness ε/Dt . Moody diagram provides a convenient method to determine the significance of pressure drop as a function of pipe's relative roughness.

A number of experimental studies [4, 5, 11, 12] have been reported for the calculation of the pressure drop of the sand–water slurry in horizontal pipelines. A few researchers like Kaushal et al. [13] and Parkash et al. [14, 15] have conducted experiments on glass beads with diameters of 0.125 mm and 0.44 mm through pipelines. Kaushal and Tomita [16], and Gillies et al. [17] have conducted experiments with zinc tailings slurry under different operating conditions by varying diameters, particle sizes and flow conditions. Parkash et al. [6] elucidated the slurry flow characteristics and pressure drop for 440 μm solid particulates

size slurry in horizontal pipeline with a diameter of 0.0549 m. The particulates were in the range of 10–30% solid concentration (by volume) at a Prandtl number (Pr) of 5.83. Matousek [18] performed the laboratory experiment by using sand–water mixture flow in a 0.105 m diameter pipe. The flow characteristics of the slurry flow was analyzed at three different inclinations, i.e., horizontal, vertical and 35° descendent pipes, and observed flow pattern variation for fully stratified and suspended flow. Furthermore, it is important to note that most of the experimental and numerical research reported in the area of slurry pipe flow was focused on the pressure drop, velocity distribution and concentration distribution in the slurry pipeline. Rawat et al. [19] numerically investigated the pressure drop in horizontal pipes at higher concentration of coal ash slurry. Using $k-\omega$ model, it was evaluated that the pressure drop is the function of the flow velocity, at high concentration pressure drop decreases while the flow velocity increases. Moreover, Kaushal et al. [13] conducted experiments on glass beads with diameters of 0.44 mm and 0.125 mm having an equal concentration with water, i.e., 50% (v/v). It was revealed that the pressure drop varies with the efflux concentration and slurry velocity. However, only the pressure drop of the mixture was measured. From the literature, it was observed that the parameters (i.e., settling velocity and concentration distribution) of particles of different sizes in a multi-sized slurry have neither been measured experimentally nor obtained by numerical simulation.

In the recent decades, there is a continuous advancement in slurry pipeline transport. But, most of the work [13, 16, 18, 20] seems to be limited to the investigation of pressure drop, critical velocity, flow rate and solid concentration. For metal pipe tube to concrete pipes [9], a number of models have already been developed which were found to be highly successful to estimate the desired objectives. The past researches have also revealed about some of the limitations of the present models, like difficulty to predict values at extensive locations, limitation to use multiple equipment to monitor the slurry behavior (like solid profile, concentration, pressure and so on) while calculating the terms like settling velocity, granular pressure, granular temperature and specific energy consumption.

In order to calculate the settling/deposition velocities, most of the European dredging industry uses the Durand formula [21], which is based on experimental data, whereas American industries widely use the Wilson formulas [22–24]. Ekambara et al. [25] predicted the behavior of horizontal solid–liquid pipeline flows under a wide range of conditions using a two-fluid model in ANSYS-CFX, and simulation results were validated with the experimental results. Wu et al. [26] presented the methods for improving the energy efficiency into slurry transportation for low viscous Newtonian slurries. The experimental analysis clearly showed that energy per unit solid mass varies with solid concentration

and specific energy is minimized by using suitable concentration, i.e., 20–30% (v/v). In addition, specific energy was found to decrease with change in the equipment size, i.e., pipe diameter and tank size.

Most of the researchers like [27, 28] centralized the idea of predicting the pressure loss and minimum settling velocity for safe transportation while considering some other influential parameters like rheological characteristics, flow velocity and particle shape. The phenomena of pressure gradient reported into most of the literature [14, 15, 29] to determine the specific energy consumption required for choosing pumps and to optimize the pipeline design parameters, i.e., pipe diameter, roughness and volume fraction. Pullum and McCarthy [28] combines the specific energy data sets from 20 publication for high concentration coarse particles mixing with non-Newtonian carrier (fly ash). It was established that slurry mixture at more than 40% v/v solid concentration, conveyed at low velocity, demonstrates lower specific energy consumption (SEC) compared to the requirement for conventional dilute solids phase systems. The key advantages of such higher concentration are its inherent stability and ease in start or stop in the pipelines. Schaan et al. [27] studied about the multiple slurries (sand, glass) with water composition. It was observed that the pipe friction increases with the angularities of particles. That means, higher specific energy consumption is required to move sharp edged particles as compared to round glass particles. Li et al. [30] studied the particle interaction for 125- and 440-micron particle with varying solid concentration and flow condition. It was observed that variation in solid concentration and flow velocity leads to change in different flow properties, i.e., velocity profile, concentration profile and wall shear stress.

A lot of research has been carried out in past for pressure drop, velocity distribution, but there is a dearth in literature for effect of roughness height, wall shear stress, rise in temperature, settling velocity, specific energy consumption, pressure distribution along the flow and many more. It is evident that the roughness height and the concentration of the particles have a significant influence on the slurry flow through a pipe. Therefore, it is crucial to explore the slurry flow behavior at different roughness heights and particle concentration range. The objective of this paper is to investigate the effect of roughness height on pressure distribution, pressure drop, velocity profiles at different concentrations and flow velocities. The standard Eulerian RNG k-epsilon multiphase model is used for modeling and simulation. Furthermore, pressure and temperature distribution for different particle sizes at different velocity and solid concentration have been established. Important transport properties like flow velocity, wall shear stress distribution and change in their trend at different flow velocity and solid concentration range are also evaluated. In addition, settling velocity for variety of particle sizes with different solid concentration at

different Prandtl fluids is evaluated. The effect of different solid concentration and Prandtl number on particle's Specific energy consumption phenomenon for different particle size are also assessed.

2 Mathematical Modeling

2.1 Governing Equations

The governing equations used in the simulation are described as below [31]:

2.2 Continuity Equation

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla(\alpha_f \rho_f v_f) = \sum_{p=1}^n (\dot{m}_{pf} - \dot{m}_{fp}) + S_s \quad (1)$$

where $\alpha_p \rho_p$ and $\dot{m}_{pf}$, $\dot{m}_{fp}$ represent the discrete phase density and mass transformation from particulates to fluid/fluid to particulates, respectively.

2.3 Momentum Equations

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_f \rho_f \vec{U}_f) + \nabla(\alpha_f \rho_f \vec{U}_f \vec{U}_f) \\ = -\alpha_f \nabla p + \nabla \bar{\tau}_f + \alpha_f \rho_f \vec{g} + K_{pf}(\vec{V}_p - \vec{U}_f) \end{aligned} \quad (2)$$

where $\bar{\tau}_f$ and $\bar{\tau}_p$ are the phase tensor for the fluid and solid phase, respectively

$$K_{pf} = 150 \frac{\alpha_p(1 + \alpha_f)\mu_f}{\alpha_f d_p^2} + 1.75 \frac{\rho_f \alpha_p(\vec{V}_p - \vec{U}_f)}{d_p} \quad (3)$$

and K_{pf} represents the solid–fluid exchange coefficient

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_p \rho_p \vec{V}_p) + \nabla(\alpha_p \rho_p \vec{V}_p \vec{V}_p) = -\alpha_p \nabla p - \alpha_f \nabla p_p + \nabla \bar{\tau}_p \\ + \alpha_p \rho_p \vec{g} + K_{pf}(\vec{U}_f - \vec{V}_p) \end{aligned} \quad (4)$$

where

$$P_p = (\alpha_p \rho_p \theta_p) + 2\rho_p(1 + e_{pp})\alpha_p^2 g_{o,pp} \cdot \theta_p \quad (5)$$

and $g_{o,pp}$ represents the inter collision between the solid particulates

$$\bar{\tau}_p = \alpha_p \mu_p (\nabla \vec{\partial} p + \vec{\partial} p^{rr}) + \alpha_p \left(\lambda_p - \frac{2}{3} \mu_f \right) \vec{\partial} p \quad (6)$$

$$\lambda_p = 1.33(\alpha_p \rho_p d_p g_{o,pp})(1 + e_{pp}) \left(\frac{\theta_p}{\pi} \right)^{1/2} \quad (7)$$

where λ_p represents the bulk viscosity of the solid particulates

$$\mu_p = \mu_{p,col} + \mu_{p,kin} + \mu_{p,fr} \quad (8)$$

where $\mu_{p,col}$, $\mu_{p,kin}$ and $\mu_{p,bulk}$ represents the collisional, kinetic and bulk viscosities.

2.4 Turbulence Equation

The transport equations for k – ε turbulence model are expressed as:

$$\begin{aligned} \frac{\partial(\alpha_q \rho_q k_q)}{\partial t} + \nabla(\alpha_q \rho_q \vec{U}_q k_q) \\ = \nabla \left(\alpha_q \left(\mu_q + \frac{u_{t,q}}{\sigma_k} \right) \nabla k_q \right) + (\alpha_q G_{k,q} - \alpha_q \rho_q \varepsilon_q) \\ + \sum_{p=1}^n K_{pq}(C_{pq} k_p - C_{qp} k_q) - \sum_{p=1}^n K_{pq}(\vec{U}_p - \vec{U}_q) \frac{u_{t,p}}{\alpha_p \sigma_p} \nabla \alpha_p \\ + \sum_{p=1}^n K_{pq}(\vec{U}_p - \vec{U}_q) \frac{u_{t,q}}{\alpha_q \sigma_q} \nabla \alpha_q + \Pi_{kq} \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{\partial(\alpha_q \rho_q \varepsilon_q)}{\partial t} + \nabla(\alpha_q \rho_q \vec{U}_q \varepsilon_q) \\ = \nabla \left(\alpha_q \left(\mu_q + \frac{u_{t,q}}{\sigma_\varepsilon} \right) \nabla \varepsilon_q \right) + \frac{\varepsilon_q}{k_q} (C_{1\varepsilon} G_{k,q} - C_{2\varepsilon} \rho_q \varepsilon_q) + C_{3\varepsilon} \frac{\varepsilon_q}{k_q} \\ \left[\sum_{p=1}^n \left\{ K_{pq}(C_{pq} k_p - C_{qp} k_q) - \sum_{p=1}^n K_{pq}(\vec{U}_p - \vec{U}_q) \frac{u_{t,p}}{\alpha_p \sigma_p} \right\} \nabla \alpha_p \right] \\ + C_{3\varepsilon} \frac{\varepsilon_q}{k_q} \sum_{p=1}^n K_{pq}(\vec{U}_p - \vec{U}_q) \frac{u_{t,q}}{\alpha_q \sigma_q} \nabla \alpha_q + \Pi_{\varepsilon q} \end{aligned} \quad (10)$$

where $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are the $C1$, $C2$ and $C3$ epsilon number and σ_k , σ_ε are the Prandtl number having a default value of 1.0 and 1.3, respectively.

2.5 Granular Pressure Equation

Granular pressure of the solid phase is described by kinetic theory of granular flow. Equation of granular pressure is given as:

$$P^* = \rho_p \phi \theta [1 + 2\phi g_0(\phi)(1 + e)] \quad (11)$$

where $g_0(\phi)$ is defined as radial distribution function (RDF) and e is restitution coefficient. There are three common RDF ways to determine the granular pressure, named as follows:

Bagnold [32],

$$g_0(\phi) = [1 - (\phi/\phi_{\max})^{1/3}]^{-1} \quad (12)$$

Carnahan and Starling [33],

$$g_0(\phi) = \frac{2 - \phi}{2(1 - \phi)^3} \quad (13)$$

and Lun and Savage [34],

$$g_0(\phi) = (1 - \phi/\phi_{\max})^{-5\phi_{\max}/2} \quad (14)$$

where $\phi_{\max}$ is the maximum solid volume fraction of the system.

2.6 Granular Temperature Equation

Granular temperature of the solid phase is described by kinetic energy random motion method [35]. The transport equation for granular temperature is given as:

$$\frac{3}{2} \nabla(\alpha_s \rho_s \vec{v}_s \Theta_s) = (-P_s \vec{\tau} + \vec{\tau}_s) : \nabla \vec{v}_s + \nabla(k_{\Theta_s} \nabla \Theta_s) - \gamma_{\Theta_s} + \varphi_{fs} \quad (15)$$

where $(-P_s \vec{\tau} + \vec{\tau}_s) : \nabla \vec{v}_s$ is defined as energy generation by the solid stress tensor and k_{Θ_s} is diffusion coefficient modeled as:

$$k_{\Theta_s} = \frac{15d_s \alpha_s \rho_s \sqrt{\Theta_s \pi}}{4(41 - 33\eta)} \left[1 + \frac{12}{5} \eta^2 (4\eta - 3) \alpha_s g_{o,ss} + \frac{16}{15\pi} (41 - 33\eta) \eta \alpha_s g_{o,ss} \right] \quad (16)$$

$k_{\Theta_s} \nabla \Theta_s$ represents the diffusive flux of granular energy, and:

$$\eta = \frac{1}{2} (1 + e_{ss}) \quad (17)$$

γ_{Θ_s} is the collisional dissipation energy, i.e., energy dissipation rate within the solid phase due to collision between particles, defined as:

$$\gamma_{\Theta_s} = \frac{12(1 - e_{ss}^2) g_{o,ss}}{d_s \sqrt{\pi}} \alpha_s^2 \rho_s \Theta_s^{\frac{3}{2}} \quad (18)$$

φ_{fs} is defined as transfer of kinetic energy of random fluctuation in velocity of solid particle “s” and fluid phase “f,” defined as:

$$\varphi_{fs} = -3K_{fs} \Theta_s. \quad (19)$$

2.7 Settling Velocity Equation

The sedimentation of particle in a small diameter pipe is very much different from the sedimentation into free space flow [36]. An investigation to calculate the settling velocity can accurately guide about particle sedimentation in small diameter pipes. Durand equation has been considered for calculating the settling velocity with five spherical particles, whose diameter ranges from 125 to 440 micron at different solid concentration and flow velocities $V_m = 1\text{--}5 \text{ ms}^{-1}$. In the free settling, a spherical diameter of particle d_{50} , percentage solid concentration by volume v/v , C_v , gravitational constant g and pipe inside diameter D are expressed as given in Eq. 20.

$$F_L = 0.4794 + [0.5429 \times (0.01 \times C_v)^{0.1058} \times \{\log(d_{50}) - 1\}] \quad (20)$$

where F_L is the settling velocity factor

$$V_L = F_L \times \sqrt{2gD(s - s_l)/s_l} \quad (21)$$

V_L represents the setting velocity (see Eq. 21), where S and S_l are specific gravity of solid and liquid phase, respectively.

2.8 Specific Energy Consumption

It is termed as energy required to transport solid particles per unit distance through pipeline [26].

$$SEC = \frac{\frac{\Delta P}{\Delta L}}{C_v \rho_s} \quad (22)$$

where $\Delta P/\Delta L$ is termed as pressure gradient (kPa/m), ρ_s is solid particle density (kg/m^3), and C_v is volumetric solid concentration (v/v).

2.9 Prandtl Number

Prandtl number demonstrates the fluid properties in terms of momentum diffusivity (ν) and thermal diffusivity (α) ratio.

$$Pr = \frac{\nu}{\alpha} = \frac{\mu_m C_p}{K} \quad (23)$$

where Pr represents Prandtl number, μ_m is dynamic fluid viscosity, C_p represents specific heat, and K showcases thermal conductivity of fluid. The properties of fluid phase (water) at different Prandtl number are tabulated in Table 1.

3 Computational Modeling

It is quite essential to develop a mathematical model in order to look at the objective and physics of any computational problems. Mathematical modeling mainly focuses over the partial difference formulation of mass, momentum and energy conservation equations. A commercially available CFD code Fluent used for evaluating the pressure drop and settling velocity (Durand formulation) into the horizontal straight pipeline. The multiphase model consists of two, i.e., solid (glass beads) and liquid (water) phase. On the basis of ongoing research, multiple researchers [37, 38] have used Eulerian multiphase model of slurry flow in order to study the flow characteristics.

3.1 Computational Domain

ANSYS Fluent software is used to perform the simulation of multiphase slurry flow characteristics like granular temperature, granular pressure, particle settling velocity and specific energy consumption. In the present investigation, a straight pipe of mild steel having the diameter of 0.0549 m and length of 3.8 m has been considered. Mild steel demonstrates high corrosive and erosive resistivity which is essential parameter while choosing the suitable pipe material for slurry transportation. The multiphase mixture contains water (carrier fluid) as liquid phase and glass beads as a solid phase. The standard density of water at (Pr 5.83) is 997 kg/m^3 which changes accordingly with the variation in Prandtl Number (see Table 1). Additionally, density of solid phase, i.e., glass beads, is 2470 kg/m^3 , and their concentration into multiphase flow varies from $C_w = 40\text{--}60\%$ (by weight), whereas the flow velocity of mixture varies from $V_m = 1\text{--}5 \text{ ms}^{-1}$.

3.2 Boundary Conditions

The computational domain consists an inlet, outlet, wall and no slip condition for the fluid flow domain. At inlet, a multiphase flow is flowed at particular velocity and volume fraction which tends to generate the stabilized flow throughout the pipe length. The outlet section is considered as a length of 3.8 m apart from the inlet section. Figure 1 demonstrates the computational domain with inlet, outlet, wall and most importantly fully developed region (40–50 times pipe diameter). No slip condition is applied at the wall and roughness constant is fix to 0.5. Eulerian–Lagrange approach coupled with $k\text{--}\epsilon$ turbulent model for continuous fluid phase is used to carry out the simulation of glass beads slurry flow. In addition, second-order upwind scheme and SIMPLE algorithm are used in order to achieve the velocity and pressure coupling of the slurry flow. The convergence criteria of 10^{-6} were established for the present simulation.

3.3 Mesh Independency Test

The mesh independence test was conducted by choosing the different mesh geometry containing 100 k, 243, 382 k, 462 k and 522 k elements. The computational model of pipe geometry containing 462 k hexahedral elements is finalized to carry out the simulation as shown in Fig. 2a. It is found that the mesh geometry containing 462 k and 522 k elements almost gives the same results for the velocity profile as shown in Fig. 2b. Hence, the pipe geometry containing 462 k elements is finalized to carry out the simulation in order to save the computational time. The present geometric model of straight pipe was adopted from Parkash et al. [39]. Additionally, the orthogonal quality of the chosen mesh geometry is 0.934, which is very high in the present case.

Fig. 1 Flow domain

Table 1 Fluid properties of liquid phase at different Prandtl number [6]

Prandtl number (Pr)	Density (kg/m^3)	Viscosity (kg/m s)	Specific heat (KJ/Kg K)	Thermal conductivity (W/mK)
1.34	937	0.000217	4.256	0.688
2.14	973	0.000343	4.199	0.671
3.42	987	0.000528	4.182	0.645
5.83	997	0.000855	4.179	0.613

Fig. 2 **a** Pipe geometry and **b** mesh independency test

3.4 Model Validation

3.4.1 Pressure Drop Validation

To validate our current model and simulation procedure, a validation case for particulate size 125-micron and 440-micron particle at $C_{vf} = 30$ was simulated against a published work of Kaushal et al. [40], and can be seen in Fig. 3a, b, respectively. It is found that our simulation results are consistent with the experimental results of Kaushal et al. [40]. Furthermore, it can be seen that there is a negligible difference between the simulated and experimental pressure drop

Table 2 Validation of present wall shear stress with Li et al. [30]

Constraints (125-micron particle)	Present study	Li et al. [30]	Percentage error
At $V_m = 2 \text{ ms}^{-1}$ and $C_{vf} = 20\%$	6.030	5.973	0.94%
At $V_m = 4 \text{ ms}^{-1}$ and $C_{vf} = 20\%$	23.590	24.062	2.00%

at low velocity range 1 and 2 ms^{-1} . However, for the velocity range of 3–5 ms^{-1} , a slight deviation in the simulated and experimental pressure drop profile can be noticed, but they follow almost similar trend.

3.4.2 Wall Shear Stress Validation

The obtained simulated results of wall shear stress for 125-micron particle at $C_{vf} = 20\%$ are validated with the existing results of the literature by Li et al. [30]. The findings show that the developed computational model results are in good agreement (the error of within 2%) with the existing results of the literature. The comparison of the present and the existing results is shown in Table 2.

4 Computational Results

4.1 Granular Pressure Contours

4.1.1 Granular Pressure for 125-Micron Particle Size

Figure 4a–c depicts the granular pressure (Pa) also named as collisional particle pressure, contours at outlet section of

Fig. 3 Computational model validation with Kaushal et al. [40] at $C_{vf} = 30\%$ for **a** 125-micron and **b** 440-micron

Fig. 4 Granular pressure (Pa) for 125-micron particle at $V_m = 1$ – 5 ms^{-1} for solid concentrations, **a** $C_w = 40\%$; **b** $C_w = 50\%$; and **c** $C_w = 60\%$

Fig. 5 Granular pressure for 440-micron particle at $V_m = 1\text{--}5\text{ ms}^{-1}$ for solid concentrations, **a** $C_w = 40\%$; **b** $C_w = 50\%$; and **c** $C_w = 60\%$

(a) at $C_w = 40\%$

(b) at $C_w = 50\%$

(c) at $C_w = 60\%$

the straight pipeline for 125-micron particle size at different solid concentration ranges, $C_w = 40\text{--}60\%$ (by weight) at mean flow velocity, $V_m = 1\text{--}5\text{ ms}^{-1}$. It is quite obvious from Fig. 4a–c that the sedimentation largely occurs in the lower half section of the pipeline especially at the bottom of the pipeline due to gravitational effect. For $C_w = 40\%$, at low mean flow velocity, i.e., at $V_m = 1\text{ ms}^{-1}$, the granular pressure is found more near the bottom of the pipeline as shown in Fig. 4a. However, as the velocity rises to 2 ms^{-1} , the maximum granular pressure spot merely observed about the bottom of the pipeline. Further, it can be seen that as the velocity rises from 3 to 5 ms^{-1} , the sedimentation seems to escalate along the pipe sidewalls away from the pipe bottom and the maximum granular pressure spots are symmetrical about the bottom of the pipeline. Furthermore, the same effect can also be seen at $C_w = 50\%$ and at $C_w = 60\%$ as described in Fig. 4b, c, respectively. However, with increase in concentration from 40 to 60%, the momentum exchange between the flowing particles increases [6], which enhances the turbulence intensity [41], and thereby, the granular pressure steered toward the sidewalls of the pipeline as depicted in fig at $C_w = 60\%$. Moreover, it is important to note that the granular pressure increases with increase in mean flow velocity ($V_m = 1\text{--}5\text{ ms}^{-1}$) at all concentration range, $C_w = 40\text{--}60\%$. The present results are consistent with the results of Parkash et al. [39] and Li et al. [30] for $V_m = 1\text{--}4\text{ ms}^{-1}$ with solid concentration range $C_{vf} = 20$ and 40%.

4.1.2 Granular Pressure for 440-Micron Particle Size

Figure 5 shows 440-micron particle granular pressure (Pa) contours at outlet section of the pipeline for solid concentration range, $C_w = 40\text{--}60\%$ (by weight) and at mean flow velocity range, $V_m = 1\text{--}5\text{ ms}^{-1}$. It is interesting to see that the pressure distribution for 440-micron particle size deviates significantly from that of 125-micron. For instance, at low concentration, i.e., $C_w = 40\%$, the maximum granular pressure occurs at the bottom of the pipeline due to large sedimentation at the pipeline bottom because of the gravitational effect. At low velocity, $V_m = 1\text{ ms}^{-1}$, the granular pressure is comparatively less as illustrated in Fig. 5a. However, as the velocity rises from 2 to 5 ms^{-1} the maximum granular pressure increases and remains maximum in the pipe bottom but, as the velocity rises, the granular pressure starts expanding toward the sidewalls of the pipeline as well. Furthermore, the similar effect can be seen for the chosen velocity at solid concentration range, $C_w = 50\text{--}60\%$ as depicted in Fig. 5b, c. It can be observed that the rise in concentration leads to increase in the magnitude of the granular pressure. For instance, it is clear from Fig. 5b, c that the pressure distribution is almost symmetrical in the pipe cross section, but there is a considerable increase in the pressure distribution along the pipe sidewalls. It can further be deduced from here that

Fig. 6 Comparison of pressure distribution b/w 125, and 440-micron particle at 10–50 roughness height and $V_m = 1\text{ ms}^{-1}$, **a** $C_w = 40\%$; **b** $C_w = 50\%$; **c** $C_w = 60\%$

with increase in concentration, the granular pressure distribution tends to cover the whole pipe cross section. This can be attributed to increase in the momentum exchange between the particles due to increase in velocity and concentration that in turn leads to increase in the flow fluctuations. Thus, the granular pressure starts developing around the whole pipe cross section. Furthermore, the obtained simulated outcomes show that the granular pressure for particle size 440-micron is higher in comparison with the granular pressure obtained

Fig. 7 Variation of pressure drop at different roughness height for 125-micron particle at solid concentrations, **a** $C_w = 40\%$; **b** $C_w = 50\%$ and **c** $C_w = 60\%$

from for particle size 125-micron for the chosen solid concentration range, which is consistent with the work of Li et al. [30].

4.2 Pressure Drop Comparison in Fully Developed Region

Figure 6a–c demonstrates the variation of pressure drop at fully developed flow region (2.4–3.8 m) for 125-micron and 440-micron particle at roughness height of 10–50 micron with mean flow velocity of $V_m = 1 \text{ ms}^{-1}$. The region behind choosing this velocity is, in lower velocity the difference in results are much more clear as compared to higher velocity. It is interesting to see that pressure falls significantly from 2.4 m toward the outlet of pipe. From Fig. 6a–c, it can be seen that the smaller particle, i.e., 125-micron demonstrates lower pressure variation compared to large particles, i.e., 440-micron. This can be attributed to the fact that the large particle increases the mass fraction, which alters density of mixture. This in turn leads to the accumulation of particles in the wall, and ultimately causes higher resistance (frictional) and rubbing forces in the flow [42]. However, at low concentration, i.e., $C_w = 40\%$, the pressure distribution is lower (can be

seen in Fig. 6a) as compared to higher concentration, $C_w = 50\text{--}60\%$ can be seen in Fig. 6b, c, respectively. However, the viscosity in slurry flow increases with concentration, which alters the corresponding density and Reynolds number (leads to accumulation of ice particles into the wall) [43]. Furthermore, for a wide range of velocity, $V_m = 1\text{--}5 \text{ ms}^{-1}$, the pressure trend was found to be almost similar to Fig. 6a, b with their respective concentrations. Therefore, the pressure variation for only one velocity value is presented. In addition, it was observed that roughness height considerably influences the pressure variation for 125-micron particle (can be seen in Fig. 6c). However, for 440-micron particle the roughness height was found to have relatively little effect on the pressure variation. This can be ascribed to the particle size, as it is almost 10–30% larger than pipe wall roughness in case of 440-micron particle.

4.3 Effect of Roughness Height on Pressure Drop

Figure 7a–c demonstrates the variation of pressure drop at different roughness height for 125-micron particle size in x – y plane at wide mean flow velocity range, $V_m = 1\text{--}5 \text{ ms}^{-1}$ and solid concentration range, $C_w = 40\text{--}60\%$. It is found that

Fig. 8 Variation of pressure drop at different roughness height for 440-micron particle at solid concentrations, **a** $C_w = 40\%$; **b** $C_w = 50\%$ and **c** $C_w = 60\%$

the pressure drop increases with rise in flow velocity at all the efflux concentration range. However, at 10-micron roughness height, the difference in pressure drop at velocities, i.e., $V_m = 1\text{--}2 \text{ ms}^{-1}$, is comparatively small than the pressure drop at higher velocities, i.e. $3\text{--}5 \text{ ms}^{-1}$. The findings further reveal that there is not any significant change in pressure drop at higher concentration for each roughness height. This could be occurred due to larger particles at higher velocity and larger concentration does not settle earlier (see Sect. 4.9). Furthermore, the findings obtained through simulated outcomes show that the trend of pressure drop with different roughness height at different velocity range is nearly parallel for the chosen solid concentration range, $C_w = 40\text{--}60\%$. In addition, the same effect of the pressure drop at different roughness height for chosen velocity range can also be seen for 440-micron particle size as depicted in Fig. 8a–c.

Figure 9 demonstrates, the comparison of pressure drop at roughness height 10–50 micron for 125- and 440-micron particle size in a given mean flow velocity $V_m = 4$ and 5 ms^{-1} and solid concentration $C_w = 40\%$. It is clearly seen that larger particle demonstrates higher pressure gradient in com-

Fig. 9 Comparison of roughness height effect on pressure drop for 125- and 440-micron particle at $C_w = 40\%$ and $V_m = 4\text{--}5 \text{ ms}^{-1}$

parison with smaller particle. This can be corroborated with Sect. 4.2. As the velocity rises the value of pressure gradient significantly rises.

4.4 Granular Temperature Contours

4.4.1 Granular Temperature for 125-Micron Particle Size

Figure 10 depicts contours of granular temperature at outlet section of the pipeline for 125-micron particle size at solid concentration ranges, $C_w = 40\text{--}60\%$ (by weight) and mean flow velocity range, $V_m = 1\text{--}5\text{ ms}^{-1}$. It is interesting to see that the temperature distribution follows almost similar trend as followed by the pressure. It could be due to the collision of particle leads to rise in temperature [14]. It can be seen that the granular temperature is maximum near the bottom and minimum at the sidewalls of the pipeline. At low velocity, i.e., $V_m = 1\text{ ms}^{-1}$, the magnitude of the granular temperature is maximum near the bottom as represented in Fig. 10a. However, as the velocity rises from 2 to 5 ms^{-1} , the magnitude of the granular temperature increases and steer to the sidewalls of the pipeline. Increase in granular temperature leads to rise in wall shear stress. In the similar manner, the granular temperature can also be seen following the pressure contours for $C_w = 50$ and 60% (except at $V_m = 1\text{ ms}^{-1}$) as shown in Fig. 10b, c, respectively. The granular temperature increases with increase in the flow velocity as the velocity of the particles increases, the flow fluctuations increases rapidly and there is rapid collision of the particles causes rise in temperature. Furthermore, there is rise in temperature with concentration as the increase in particles correspondingly increase the flow turbulence which in turn, rises the temperatures due to increase in friction.

4.4.2 Granular Temperature for 440-Micron Particle Size

Figure 11 presents the granular temperature distribution contours at outlet section of the pipeline for 440-micron particle at solid concentration range, $C_w = 40\text{--}60\%$ (by weight) and mean flow velocity range, $V_m = 1\text{--}5\text{ ms}^{-1}$. Similar to pressure distribution, the temperature distribution for 440-micron varies considerably from that of 125-micron particle. It has been found that maximum granular temperature occurs at the bottom and sidewalls of pipeline. At low velocity, i.e., $V_m = 1\text{ ms}^{-1}$, the maximum temperature occurs at the sidewalls of the pipeline as depicted in Fig. 11a at $C_w = 40\%$. However, as the velocity rises from 2 to 5 ms^{-1} , the granular temperature excels at the bottom as well as sidewalls of the pipeline. This may be occurred due to friction effect of solid particles with the pipe wall; at higher flow velocity, the friction effect is more. Higher friction effect leads to temperature rise and start developing wall shear stress over the walls. Further, at higher concentrations, i.e., at $C_w = 50$ and 60% as shown in Fig. 11b, c, respectively, the granular temperature influences the larger circumferential area of the pipe. It occurs because of higher concentration leads to increase in the particle percentage into slurry flow and makes slurry mixture denser.

Denser fluid showcases higher frictional and rubbing effect [42]. Further, the rise in temperature of granular materials results due to increase in mean flow velocity of the particle and solid concentration, which enhance the turbulence due to particle inter collisions and particle wall collision and thereby led to increase in temperature through the pipe domain. Furthermore, it is observed that the granular temperature experienced by the 440-micron particle sizes is more in comparison with the granular temperature for 125-micron particle sizes for the chosen velocity and solid concentration range. Larger particles have relatively higher momentum and their collision or rubbing with wall or other particles leads to temperature rise in slurry flow.

4.5 Velocity Distribution

Figure 12a–c shows the velocity profile for 125-micron particle size at the mean flow velocity range, $V_m = 1\text{--}5\text{ ms}^{-1}$ and solid concentration range, $C_w = 40\text{--}60\%$. It is found that at low velocity, $V_m = 1\text{ ms}^{-1}$ and solid concentration, $C_w = 40\%$ the velocity profile is almost flat in nature as shown in Fig. 12a. However, as the velocity and solid concentration increases, the flatten nature of the velocity profile diminishes as shown in Fig. 12b, c. Further, the same effect can also be seen for 440-micron particle size at the chosen velocity and solid concentration range as depicted in Fig. 13a–c. Moreover, the velocity profile for 440-micron solid particle size is more parabolic in comparison the velocity profile for 125-micron particle size. At higher concentration $C_w = 50$ and 60% , the profile is much more turbulent in nature; it occurs due larger particle showcases more turbulence effect [44]. The abrupt shape in velocity profile at higher concentration occurs due to larger turbulence effect for 440-micron particle.

4.6 Velocity Profile Variation at Different Roughness Height

The glass beads velocity profile in last one-meter length of the pipeline at different roughness height (10–50 micron) for 125-micron and 440-micron particle size is depicted in Fig. 14a, b, respectively. It is found that the velocity profile is much more parabolic in nature for larger particle at different roughness heights. Further, the findings also reveal that the change in roughness height does not have a significant effect on the velocity profile for the chosen velocity and concentration range.

4.7 Velocity Vector Profile

Figure 15 demonstrates the vector representation of velocity profile at fully developed region for 125-micron particle having mean flow velocity $V_m = 1\text{ ms}^{-1}$. It is clearly seen that at

Fig. 10 Granular temperature for 125-micron particle at $V_m = 1\text{--}5\text{ ms}^{-1}$ for solid concentrations, **a** $C_w = 40\%$; **b** $C_w = 50\%$; and **c** $C_w = 60\%$

Fig. 11 Granular temperature for 440-micron particle at $V_m = 1$ – 5 ms^{-1} for solid concentrations, **a** $C_w = 40\%$; **b** $C_w = 50\%$; and **c** $C_w = 60\%$

Fig. 12 Velocity profile for 125-micron particle at solid concentration, **a** $C_w = 40\%$, **b** $C_w = 50\%$, **c** $C_w = 60\%$

Fig. 13 Velocity profile for 440-micron particle at solid concentration, **a** $C_w = 40\%$, **b** $C_w = 50\%$, **c** $C_w = 60\%$

Fig. 14 Velocity profile for roughness height 10–50 micron at $V_m = 5 \text{ ms}^{-1}$ and $C_w = 60\%$, **a** 125-micron particle, **b** 440-micron particle

Fig. 15 Velocity vector profile in fully developed flow region for 125-micron particle at $V_m = 1 \text{ ms}^{-1}$ and solid concentrations, **a** $C_w = 40\%$, **b** $C_w = 50\%$ and **c** $C_w = 60\%$

fully developed flow region, the velocity profile become symmetrical. Larger length vector demonstrates higher velocity, which occurs at the center of the pipe and continuously reduces toward the pipe walls. The similar velocity profile is already demonstrated in (Fig. 12a–c). For $C_w = 40\%$, the higher velocity occurs at the center but distributed over a large circumferential region of the pipe (see Fig. 15a), and as the concentration rises, the higher velocity remains concentrated near the centerline (can be seen Fig. 15b, c) due to higher turbulence effect.

Similarly, for 440-micron particle (see Fig. 16), the larger velocity (long length vector) presented in center and minorly decreases toward the upper wall and extensively towers lower wall. This is because larger particle is in suspension at lower velocity. The similar velocity profile is showcased on Fig. 13a–c. As solid concentration rises toward higher concentration, the velocity profile is restricted toward the center (see Fig. 16b, c).

Fig. 16 Velocity vector profile in fully developed flow region for 440-micron particle at $V_m = 1 \text{ ms}^{-1}$ and solid concentrations, **a** $C_w = 40\%$, **b** $C_w = 50\%$ and **c** $C_w = 60\%$

4.8 Wall Shear Stress Distribution

Figure 17a–c demonstrates the simulated wall shear stress for secondary solid phase (125-micron particle) at mean flow velocity $V_m = 1\text{--}5 \text{ ms}^{-1}$ and solid concentration range, $C_w = 40\text{--}60\%$ (by weight). Figure 17a shows wall shear stress for glass beads slurry having 125-micron size at velocity $V_m = 1\text{--}5 \text{ ms}^{-1}$ with $C_w = 40\%$ concentration from inlet to outlet section. It can be seen that the maximum shear stress occurs at the bottom of the pipe due to large sedimentation because of gravitational effect, and minimum at the top of the pipe. Our results are in good agreement with the work of Li et al. [44], who have investigated the wall shear stress for 125-micron at $C_w = 20\text{--}50\%$ and $V_m = 2\text{--}5 \text{ ms}^{-1}$. At low velocity, $V_m = 1\text{--}2 \text{ ms}^{-1}$ the wall shear stress is localized at the bottom of the pipe, and starts expanding toward the pipe sidewalls. In addition, granular pressure and granular temperature (Sects. 4.1.1 and 4.4.2) are mainly localized at the bottom of the pipe due to rubbing, frictional force which ultimately increase the wall

Fig. 17 Wall shear stress distribution for 125-micron particle at $V_m = 1\text{--}5\text{ ms}^{-1}$ for solid concentrations, **a** $C_w = 40\%$, **b** $C_w = 50\%$ and **c** $C_w = 60\%$

(a) at $C_w = 40\%$

(b) at $C_w = 50\%$

(c) at $C_w = 60\%$

Fig. 18 Wall shear stress distribution for 440-micron particle at $V_m = 1\text{--}5\text{ ms}^{-1}$ for solid concentrations, **a** $C_w = 40\%$, **b** $C_w = 50\%$ and **c** $C_w = 60\%$

(a) at $C_w = 40\%$

(b) at $C_w = 50\%$

(c) at $C_w = 60\%$

Fig. 19 Prediction of settling velocity with different particle sizes at solid concentrations range, **a** $C_w = 40\%$, **b** $C_w = 50\%$, and **c** $C_w = 60\%$

shear stress for given velocity and concentration range. Furthermore, at high velocity $V_m = 3\text{--}5\text{ ms}^{-1}$ solid particles are suspended with carrier fluid, which increases wall shear stress at the sidewalls due to rubbing and collision of particles with pipe wall surface. In addition, the effect of wall shear stress increases proportionally with the mean flow velocity.

The similar trend is followed by $C_w = 50$ and 60% solid concentrations, depicted in Fig. 17b, c. At low velocity, the maximum wall shear stress occurs at the bottom and expands toward the sidewalls with rise in mean flow velocity. The wall shear stress for $C_w = 60\%$ is relatively higher than low solid concentration, i.e., $C_w = 40\text{--}50\%$. This happens because higher concentrations of the particles in flow cause higher flow fluctuations which ultimately result into more intense rubbing, frictional and collision forces. Subsequently, there is a rise in the wall shear stresses [30].

Figure 18a–c demonstrates the wall shear stress distribution for secondary solid phase (440-micron particle size) at mean flow velocity $V_m = 1\text{--}5\text{ ms}^{-1}$ for a solid concentration range, $C_w = 40\text{--}60\%$ (by weight). The maximum wall shear stress is localized at the bottom for low velocity ($V_m = 1\text{--}2\text{ ms}^{-1}$), and at higher velocities ($V_m = 3\text{--}5\text{ ms}^{-1}$), the

shear stress expands toward the sidewalls. Higher concentration of granular pressure and temperature (Sects. 4.1.2, 4.4.2) clearly shows that maximum rubbing and friction forces are developed at the bottom and pipe side walls, which ultimately causes an increase in the wall shear stress. It arises due to rubbing and friction of solid particles with pipe wall. For every solid concentration, i.e., $C_w = 40\text{--}60\%$, the wall shear stress follows similar trend which is depicted in Fig. 18a–c, respectively. Furthermore, higher solid concentration demonstrates higher value of wall shear stress. It occurs because larger and dense solid particles are suspended and move with carrier fluid, which strikes the pipe wall and generates the wall shear stress.

In addition, the comparison of Figs. 17 and 18 revealed that the larger particle possess higher wall shear stress than smaller size particles. It can be attributed to the higher momentum generation by the larger particle while moving.

4.9 Particle Size Influence on Settling Velocity

Figure 19a–c demonstrates the settling velocity for different particle sizes for solid concentration range, $C_w = 40\text{--}60\%$, which is calculated using Eq. (20–21) at different Prandtl

Fig. 20 Effect of particle size on settling velocity at different solid concentrations

numbers, i.e., 1.34, 2.14, 3.42 and 5.83. The findings show that the settling velocity increases with increase in particle sizes for the chosen Prandtl fluids range. For instance, the particle size 125-micron exhibits less settling velocity in comparison with particle size 440-micron. Therefore, it is found that fluid properties at different Prandtl number have a significant effect on settling velocity of particle, i.e., at high

Prandtl number (5.83), the settling velocity is minimum compared to others. The difference between settling velocity at low Prandtl number (1.34) is more substantial than the high one (5.83). From Fig. 19a–c, we can see that settling velocity for every Prandtl number follows approximately similar trend at all efflux solid concentration range.

4.10 Concentration Influence on Settling Velocity

Figure 20 shows the effect of solid concentration on settling velocity for different particle sizes and Prandtl number, 1.34. The findings show that the settling velocity increases with increase in particle size and solid concentration. Further, the trend of settling velocity obtained at different volumetric concentrations for chosen particle size is same.

4.11 Specific Energy Consumption

The specific energy consumption (SEC) is calculated using Eq. 22, and plotted against mean flow velocity as shown in Fig. 21. It can be seen from the curve that the SEC increases proportionally with the velocity increment. The low Prandtl number, i.e., 1.34, demonstrates higher SEC compared to

Fig. 21 Specific energy consumption for different Prandtl number at solid concentrations, **a** $C_w = 40\%$, **b** $C_w = 50\%$ and **c** $C_w = 60\%$

Fig. 22 Comparison of SEC for different particle sizes at $C_w = 40\%$

other, i.e., more energy is required to lift the particle in fluid domain. The Prandtl number has a significant effect on the carrier fluid properties, as low Prandtl number displays less density and viscosity of the carrier fluid. The minimum SEC appears at low volumetric concentrations ($C_w = 40\%$) as depicted in Fig. 21a. However, for higher concentrations, i.e., $C_w = 50$ and 60% , as the mean flow velocity increases the SEC curve for low Prandtl number also increases drastically (can be seen at Fig. 21b, c). Therefore, the more efficient way to transport the slurry through pipeline is at low velocity and higher Prandtl number. The SEC curve follows similar trend demonstrated by Wu et al. [26] for 200-micron particle size. Furthermore, the SEC at different velocity for particle sizes 125, 200, 275, 350 and 440-micron is shown in Fig. 22. It is found that SEC increases with increase in particle size at the given velocity range.

5 Conclusion

The simulated outcomes obtained from developed computational model through horizontal slurry pipeline are summarized as below:

- The obtained simulated outcomes show that the pressure drop increases with increase in pipe roughness for the chosen velocity, concentration and Prandtl number range. The pressure drop experienced by 440-micron particle size is more than 125-micron particle size at different roughness height. The pressure drop at roughness height 50-micron is more followed by 40-micron, 30-micron, 20-micron and 10-micron for both 125-micron and 445-micron particle sizes.
- The maximum granular pressure is found more near the bottom of the pipeline and it is found that the granular pressure increases with increase in mean flow velocity ($V_m = 1\text{--}5 \text{ ms}^{-1}$) at all concentration range, $C_w = 40\text{--}60\%$.

Moreover, the granular pressure for particle size 440-micron is higher in comparison with the granular pressure obtained from for particle size 125-micron for the chosen solid concentration range.

- Pressure drop experienced at fully developed region for 440-micron particle is more than 125-micron particle for 10–50-micron roughness height at every available concentration and velocity range. The variation of pressure drop into 125-micron particle at different roughness height is more than 440-micron particle.
- The granular temperature is maximum near the bottom and minimum at the sidewalls of the pipeline. At low velocity, the magnitude of the granular temperature is maximum near the bottom. However, with increase in velocity the magnitude of the granular temperature increases and steer toward the sidewalls of the pipeline. Moreover, the granular temperature experienced by 440-micron particle sizes is more compared to 125-micron particle sizes.
- As solid concentration rises $C_w = 40\text{--}60\%$, the velocity profile becomes more parabolic in shape. For large particle, i.e., 440-micron, the velocity profile does not make any symmetric profile. The maximum flow velocity is developed at the center of pipe. The similar trend is also demonstrated by vector profile. The larger vector are demonstrated in center where velocity is maximum at continuously reduced toward pipe wall.
- The effect of roughness height for any chosen concentration and velocity range does not make any significant effect on velocity profile.
- Wall shear stress increases with increase in mean flow velocity and solid concentration. The similar trend is followed for 125- and 440-micron particle. The coarse particle, i.e., 440-micron, demonstrates larger wall shear stress compared to small size particle for given velocity and solid concentration range.
- The settling velocity of particle increases with increase in particle size at different Prandtl number. The particle flowing at lower Prandtl fluid requires more velocity to keep particle in suspension in the computational domain.
- The settling velocity of particle also increases with increase in particle size at all the solid concentration range.
- The specific energy consumption increases with increase in flow velocity at given solid concentration and Prandtl fluid. The higher energy efficiency is obtained at the larger Prandtl number. Furthermore, SEC increases with increase in particle size at the given velocity range and solid concentration range.

Therefore, it is recommended that in order to design the efficient slurry pipeline system the slurry must be transported at low velocity and high Prandtl number.

References

- Singh, J.P.; Kumar, S.; Mohapatra, S.K.: Modelling of two phase solid-liquid flow in horizontal pipe using computational fluid dynamics technique. *Int. J. Hydrogen Energy* **42**, 20133–20137 (2017). <https://doi.org/10.1016/j.ijhydene.2017.06.060>
- Singh, J.; Kumar, S.; Singh, J.P.; Kumar, P.; Mohapatra, S.K.: CFD modeling of erosion wear in pipe bend for the flow of bottom ash suspension. *Part. Sci. Technol.* **37**, 275–285 (2019). <https://doi.org/10.1080/02726351.2017.1364816>
- Babcock, H.A.: Heterogeneous flow of heterogeneous solids. In: *Advances in Solid Liquid Flow in Pipes and its Applications* pp. 125–148 (1971)
- Carleton, A.J.; French, R.J.; James, J.G.; Broad, B.A.; Sreat, M.: Hydraulic transport of large particles using conventional and high concentration conveying. In: *Proceedings of Hydrotransport (1978)*
- Cnhabra, R.; Richardson, J.F.: Hydraulic transport of coarse gravel particles in a smooth horizontal pipe. *Chem. Eng. Res. Des.* **61**, 313–317 (1983)
- Parkash, O.; Kumar, A.; Sikarwar BS.: CFD modeling of slurry pipeline at different Prandtl numbers. *J. Therm. Eng.* **7**, 951–969 (2021)
- Darcy, H.: *Recherches Expérimentales Relatives au Mouvement de l'eau dans les tuyaux*, Mallet-Bachelier (1857)
- Fanning, J.T.: *A Practical Treatise on Hydraulic and Water-Supply Engineering: Relating to the Hydrology, Hydrodynamics, and Practical Construction of Water-Works, in North America*, D. Van Nostrand Company (1906)
- Colebrook, C.F.; Blench, T.; Chatley, H.; Essex, E.H.; Finnicome, J.R.; Lacey, G.; Williamson, J.; Macdonald, G.G.: Correspondence turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws (includes plates). *J. Inst. Civ. Eng.* **12**, 393–422 (1939). <https://doi.org/10.1680/jjoti.1939.14509>
- Moody, L.F.: Friction factors for pipe flow. *Trans. ASME*. **66**, 671–684 (1944)
- Ravelet, F.; Bakir, F.; Khelladi, S.; Rey, R.: Experimental study of hydraulic transport of large particles in horizontal pipes. *Exp. Thermal Fluid Sci.* **45**, 187–197 (2013). <https://doi.org/10.1016/j.expthermfluidsci.2012.11.003>
- Najmi, K.; Hill, A.L.; McLaury, B.S.; Shirazi, S.A.; Cremaschi, S.: Experimental study of low concentration sand transport in multiphase air–water horizontal pipelines. *J. Energy Resour. Technol.* (2015). <https://doi.org/10.1115/1.4029602>
- Kaushal, D.R.; Sato, K.; Toyota, T.; Funatsu, K.; Tomita, Y.: Effect of particle size distribution on pressure drop and concentration profile in pipeline flow of highly concentrated slurry. *Int. J. Multiph. Flow* **31**, 809–823 (2005). <https://doi.org/10.1016/j.ijmultiphaseflow.2005.03.003>
- Parkash, O.; Kumar, A.; Sikarwar, B.S.: CFD modeling of commercial slurry flow through horizontal pipeline. In: Kumar, M.; Pandey, R.K.; Kumar, V. (Eds.) *Advances in Interdisciplinary Engineering*, pp. 153–162. Springer, Singapore (2019)
- Ahmed, S.U.; Arora, R.; Parkash, O.: Flow characteristics of multiphase glass beads–water slurry through horizontal pipeline using computational fluid dynamics. *Int. J. Autom. Mech. Eng.* **16**, 6605–6623 (2019)
- Kaushal, D.R.; Tomita, Y.: Solids concentration profiles and pressure drop in pipeline flow of multisized particulate slurries. *Int. J. Multiph. Flow* **28**, 1697–1717 (2002). [https://doi.org/10.1016/S0301-9322\(02\)00047-2](https://doi.org/10.1016/S0301-9322(02)00047-2)
- Gillies, R.G.; Shook, C.A.; Xu, J.: Modelling heterogeneous slurry flows at high velocities. *Can. J. Chem. Eng.* **82**, 1060–1065 (2004). <https://doi.org/10.1002/cjce.5450820523>
- Matousek, V.: Pressure drops and flow patterns in sand-mixture pipes. *Exp. Thermal Fluid Sci.* **26**, 693–702 (2002). [https://doi.org/10.1016/S0894-1777\(02\)00176-0](https://doi.org/10.1016/S0894-1777(02)00176-0)
- Rawat, A.; Singh, S.N.; Seshadri, V.: Computational methodology for determination of head loss in both laminar and turbulent regimes for the flow of high concentration coal ash slurries through pipeline. *Part. Sci. Technol.* **34**, 289–300 (2016). <https://doi.org/10.1080/02726351.2015.1075637>
- Zouaoui, S.; Djebouri, H.; Mohammedi, K.; Khelladi, S.; Ait Aider, A.: Experimental study on the effects of big particles physical characteristics on the hydraulic transport inside a horizontal pipe. *Chin. J. Chem. Eng.* **24**, 317–322 (2016). <https://doi.org/10.1016/j.cjche.2015.12.007>
- Durand, R.; Condolios, E.; Gibert, M.: Etude expérimentale du refoulement des matériaux en conduites, en particulier des produits de dragage et des schlamms. *Journées de l'hydraulique*. **2**, 27–55 (1953)
- Wilson, K.C.; Clift, R.; Sellgren, A.: Operating points for pipelines carrying concentrated heterogeneous slurries. *Powder Technol.* **123**, 19–24 (2002). [https://doi.org/10.1016/S0032-5910\(01\)00423-5](https://doi.org/10.1016/S0032-5910(01)00423-5)
- Wilson, K.C.; Sellgren, A.: Interaction of particles and near-wall lift in slurry pipelines. *J. Hydraul. Eng.* **129**, 73–76 (2003). [https://doi.org/10.1061/\(ASCE\)0733-9429\(2003\)129:1\(73\)](https://doi.org/10.1061/(ASCE)0733-9429(2003)129:1(73))
- Wilson, K.C.; Addie, G.R.; Sellgren, A.; Clift, R.: *Slurry Transport Using Centrifugal Pumps*. Springer, Berlin (2006)
- Ekambara, K.; Sanders, R.S.; Nandakumar, K.; Masliyah, J.H.: Hydrodynamic simulation of horizontal slurry pipeline flow using ANSYS-CFX. *Ind. Eng. Chem. Res.* **48**, 8159–8171 (2009). <https://doi.org/10.1021/ie801505z>
- Wu, J.; Graham, L.; Wang, S.; Parthasarathy, R.: Energy efficient slurry holding and transport. *Miner. Eng.* **23**, 705–712 (2010). <https://doi.org/10.1016/j.mineng.2010.04.008>
- Schaan, J.; Sumner, R.J.; Gillies, R.G.; Shook, C.A.: The effect of particle shape on pipeline friction for Newtonian slurries of fine particles. *Can. J. Chem. Eng.* **78**, 717–725 (2000). <https://doi.org/10.1002/cjce.5450780414>
- Pullum, L.; McCarthy, D.J.: Ultra high concentration and hybrid hydraulic transport systems. In: *4th International Conference on Bulk Materials, Storage, Handling and Transportation: 7th International Symposium on Freight Pipelines; Preprints of Papers*, Institution of Engineers, Australia Barton, ACT, pp. 91–95 (1992)
- Skudarnov, P.V.; Lin, C.X.; Ebadian, M.A.: Double-species slurry flow in a horizontal pipeline. *J. Fluids Eng.* **126**, 125–132 (2004). <https://doi.org/10.1115/1.1637925>
- Li, M.Z.; He, Y.P.; Liu, Y.D.; Huang, C.: Effect of interaction of particles with different sizes on particle kinetics in multi-sized slurry transport by pipeline. *Powder Technol.* **338**, 915–930 (2018). <https://doi.org/10.1016/j.powtec.2018.07.088>
- Parkash, O.; Kumar, A.; Sikarwar, B.S.: Computational erosion wear model validation of particulate flow through mitre pipe bend. *Arab. J. Sci. Eng.* (2021). <https://doi.org/10.1007/s13369-021-05931-x>
- Bagnold, R.A.: Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proc. R. Soc. Lond. Ser. A Math. Phys. Sci.* **225**, 49–63 (1954)
- Carnahan, N.F.; Starling, K.E.: Equation of state for nonattracting rigid spheres. *J. Chem. Phys.* **51**, 635–636 (1969). <https://doi.org/10.1063/1.1672048>
- Lun, C.K.K.; Savage, S.B.: The effects of an impact velocity dependent coefficient of restitution on stresses developed by sheared granular materials. *Acta Mech.* **63**, 15–44 (1986). <https://doi.org/10.1007/BF01182538>
- Gidaspow, D.; Bezburuah, R.; Ding, J.: *Hydrodynamics of Circulating Fluidized Beds: Kinetic Theory Approach*. Illinois Institute

- of Technology, Chicago, IL (United States). Department of Chemical Engineering (1991)
36. Chen, J.; Li, J.: Prediction of drag coefficient and ultimate settling velocity for high-density spherical particles in a cylindrical pipe. *Phys. Fluids*. **32**, 053303 (2020). <https://doi.org/10.1063/5.0003923>
 37. Kim, C.; Han, C.: Numerical simulation of hydraulic transport of sand–water mixtures in pipelines. *Open J. Fluid Dyn.* (2013). <https://doi.org/10.4236/ojfd.2013.34033>
 38. Gopaliya, M.K.; Kaushal, D.R.: Analysis of effect of grain size on various parameters of slurry flow through pipeline using CFD. *Part. Sci. Technol.* **33**, 369–384 (2015). <https://doi.org/10.1080/02726351.2014.971988>
 39. Parkash, O.: Flow characterization of multi-phase particulate slurry in thermal power plants using computational fluid dynamics. *J. Therm. Eng.* **6**, 187–203 (2020)
 40. Kaushal, D.R.; Tomita, Y.: Experimental investigation for near-wall lift of coarser particles in slurry pipeline using γ -ray densitometer. *Powder Technol.* **172**, 177–187 (2007). <https://doi.org/10.1016/j.powtec.2006.11.020>
 41. Yarin, L.P.; Hetsroni, G.: Turbulence intensity in dilute two-phase flows—I: effect of particle-size distribution on the turbulence of the carrier fluid. *Int. J. Multiph. Flow* **20**, 1–15 (1994). [https://doi.org/10.1016/0301-9322\(94\)90002-7](https://doi.org/10.1016/0301-9322(94)90002-7)
 42. Akhtar, S.; Cheema, T.A.; Ali, H.; Kwak, M.K.; Park, C.W.: Numerical investigation of the pressure drop characteristics of isothermal ice slurry flow under variable ice particle diameter. *J. Chem.* **2020**, e6154152 (2020). <https://doi.org/10.1155/2020/6154152>
 43. Rawat, K.S.; Pratihari, A.K.: Numerical Investigation of ice slurry flow in a horizontal pipe. *IOP Conf. Ser. Mater. Sci. Eng.* **310**, 012095 (2018). <https://doi.org/10.1088/1757-899X/310/1/012095>
 44. Li, M.; He, Y.; Liu, Y.; Huang, C.: Hydrodynamic simulation of multi-sized high concentration slurry transport in pipelines. *Ocean Eng.* **163**, 691–705 (2018). <https://doi.org/10.1016/j.oceaneng.2018.06.046>