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Experimental Research Regarding the Flow Pattern and Pressure Drop in a Slurry Composed of Polypropylene-Particles

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Abstract. Pipelines used for product transportation require regular cleaning. A new method has emerged using slurry for the cleaning process, during which the flow pattern and pressure drop in the slurry are essential. The flow of slurry containing polypropylene particles was investigated using a laboratory-scale, closed-circuit pipeline facility. While the slurry was pumped, the pressure drop was measured, and the flow pattern was observed regarding particle type, slurry particle concentration, and slurry flow velocity. The results showed that after the critical flow velocity, the particles mixed uniformly with the water in the pipe, increasing the pressure drop in conjunction with the flow velocity. Although a higher particle mass fraction and small particle size reduced the critical flow velocity, the mass fraction and particle size had no significant influence on the pressure drop. This research establishes a solid foundation for the practical application of this cleaning method.

Keywords. Pipeline cleaning, experimental research, polypropylene-particles, flow pattern, pressure drop

1. Introduction

Pipelines have become the primary delivery systems for products, such as oil and gas [1, 2]. However, pipelines are polluted by debris, such as black powder [3] and wax, hindering the regular operation and causing substantial economic losses [4]. Therefore, to improve the operational pipeline conditions, regular cleaning is essential and a widely adopted industry practice.

Modern pipeline cleaning methods can be divided into chemical cleaning and physical cleaning [5]. However, these two cleaning techniques cause environmental pollution and face significant challenges in complex pipes. In recent years, a new online cleaning method has been proposed that use ice slurry, usually employed to clean water and food pipes [6, 7]. It relies primarily on the frequent and strong particle-dirt collision in the slurry flow to disintegrate the debris on the pipe wall. Since the

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slurry is recyclable and does not contain any chemical reagents, it is environmentally friendly and is not limited by the pipeline shape.

Since the debris, such as black powder and wax, in natural gas or oil pipelines is unyielding, the ice slurry is not a feasible cleaning method due to its low hardness and durability [8]. Therefore, this technique has been expanded to include a slurry consisting of polypropylene particles and water to clean small-diameter natural gas or oil pipelines [9]. Like ice slurry, collision with polypropylene particles disintegrates the dirt on the pipe wall. Furthermore, to ensure that the particles effectively collide with debris, it is necessary to investigate the polypropylene particle distribution in the pipe. In addition, the pressure drop in the slurry during operation is essential for the design of the cleaning equipment.

Slurry flow has already been the subject of substantial experimental research and can be divided into four major flow patterns [10]: (1) A stationary bed or flow with a moving bed and saltation, (2) heterogeneous flow, (3) pseudo-homogeneous flow, (4) and homogeneous flow. Most researchers use visual observation and video recording to investigate the flow pattern of the slurry. E. Zorgani [11] examined the influence of the carrier viscosity on slurry flow patterns. F. Ravelet [12] assessed slurry consisting of large particles, revealing that particle size and specific mass significantly affect the transition point between regimes with a stationary bed and dispersed flows. Durand [13] performed extensive research involving sand, coal, and gravel slurry. He defined the critical velocity (VC) as the velocity that will not form a stationary bed with a minimum pressure drop while also investigating the influence of the concentration, pipe diameter, particle size, solid density, and liquid density on the VC. Salah Zouaoui [14] examined the flow patterns and the pressure drop of the slurry flow containing large particles in a horizontal pipe. The results indicated that below the VC, the pressure drop declines in conjunction with an increase in the flow velocity while displaying an increase above the VC. Mariella Leporini [15] investigated the flow pattern of a slurry composed of sand particles and obtained the VC of different slurry concentrations. T.C. Souza Pinto [16] used the experimental method to examine the VC of mineral slurries, while Jie Wu [17] assessed the energy efficiency of slurry flow.

The pressure drop in slurries is a complicated issue. Many researchers, such as Zand [18], Turian, and Yuan [19], and Doron, and Barnea [20], aimed to establish a model to predicate the slurry pressure drop. Lahiri and Ghanta [21] proposed a hybrid support vector regression-genetic algorithm approach to predicate the pressure drop in a solid-liquid slurry. Miedema [22] proposed a pressure-drop model for the slurry in the heterogeneous regime, which was consistent with Durand and Condolios. Amit Kumar [23, 24] investigated slurries consisting of wheat straw and corn stover agricultural waste biomass. The results indicate that the pressure drop decreases in conjunction with an increase in concentration, which differs from the conventional solid-liquid slurry. Vaseleski and Metzner [25] suggested that the pressure drop reduction in the nylon fiber slurry can be attributed to the fact that the long fibrous material dampens the turbulence. Kato and Mizunuma [26] reached a similar conclusion using an asbestos fiber slurry. S. Mellari [27] found that the pressure loss in ice slurry increases in conjunction with a higher concentration and flow velocity. Edelin [28] used an experimental method to investigate the pressure loss of a slurry composed of polypropylene particles, determining the minimum energy consumption of the slurry transportation. However, the slurry containing large polypropylene particles was not investigated.

This paper examines the flow pattern and the pressure loss of the polypropylene-particle slurry in pipes using the experimental method to understand the influence of the flow velocity, particle concentration, and particle diameter. An experimental device is designed and used to observe the flow pattern and measure the pressure loss. The experimental setup is presented in Section 2. The results are shown and discussed in Section 3. Conclusions and perspectives are provided in Section 4.

2. Experimental Setup

2.1. Test loop

An experimental device was designed to examine the flow pattern and the pressure drop of the slurry, and the test loop is shown in figure 1.

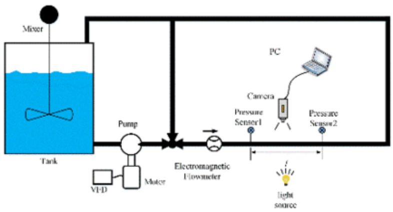

Figure 1. Sketch of the test loop.

The test loop consisted of a 100 L capacity mixing tank which was agitated using a central vertical mixer. During the experiment, the mixer blended the particles and water evenly. The outlet of the tank was connected to a centrifugal pump that pumped the slurry into the test loop. The maximum flow rate (Q_s) of the slurry was 15 m^3/h, allowing the maximum flow velocity in the measure pipeline to be 6 m/s, while the maximum pump pressure was 0.3 MPa. Particles of up to 5 mm in diameter could pass through the pump without breaking, eliminating the possibility of blockage. The pump outlet was connected to the test loop, the total length of which was L=40 m. A transparent acrylic horizontal pipe with an internal diameter of D=30 mm was located inside the test loop to observe the flow pattern of the slurry. The test loop contained another 300 L tank to recycle the slurry. The pump equipment and test loop are shown in figure 2 and figure 3.

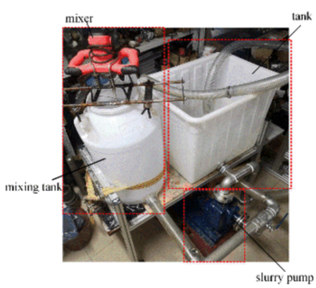

Figure 2. The picture of the experimental facilities.

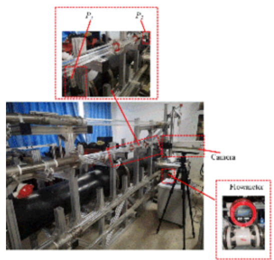

Figure 3. The picture test loop.

2.2. Experimental Material

The research specifically focused on slurry composed of polypropylene particles. The particles were classified into two groups with nominal sizes of φ3 mm and φ0.6 mm. The real solids used from the perspective of an actual application exhibited irregular shapes, as shown in figure 4, while the particle parameters are shown in table 1.

Table 1. The particle parameters.

Particle diameter(mm)	φ3	φ0.6
Density(kg/m^3)	910	910
Shore hardness	90	90

ϕ3mm ϕ0.6mm

Figure 4. The picture of the particles.

2.3. Control Parameters and Measured Quantities

This work aimed to achieve the flow pattern and the pressure drop in a horizontal pipe of the test loop regarding the flow velocity, particle concentration, and particle size. The mass fraction of the polypropylene particles in the slurry (see Eq. (1)) was determined during the experiment (C_m was the mass fraction, m_p was the mass of the particles, ρ_w was the density of the water, and V_w was the volume of the water). Four particle mass fractions (5%, 10%, 15%, and 20%) were selected for the experiment.

$$C_m = \frac{m_p}{m_p + \rho_w V_w} \tag{1}$$

During the experiment, a mixer was used to blend the particles and water evenly. The centrifugal pump was connected to an induction electric motor and controlled by a variable frequency drive (VFD) controller. The VFD could adjust the Q_s of the pump, eliminating the need for the test loop to have a flow control valve that might cause particle blockage in the pipeline. An electromagnetic flowmeter was installed in the test loop to measure the Q_s of the slurry. Two pressure sensors were placed in the test loop at a distance of l =1.2 m to record the slurry pressure drop. The parameters of the electromagnetic flow meter and the pressure sensor are shown in table 2. All the sensors were connected to a computer via a data recording system. The flow velocity and pressure drop were calculated at meter intervals using Eq. (2) and Eq. (3). A recording camera was installed in the pipe with a recording distance of 0.5 m to record the flow pattern of the slurry. A light source was placed near the camera, and the parameters are shown in table 3.

$$V = \frac{Q}{S} \tag{2}$$

$$\frac{\Delta P}{l} = \frac{P_1 - P_2}{l} \tag{3}$$

Table 2. The parameters of the sensors.

	Range	Accuracy	Voltage
Flowmeter	0~30m^3/h	0.3%	220V
Pressure sensor	0~0.1MPa	0.2%	24V

Table 3. The parameters of the video.

Resolution	Sample Rate(fps)	Range
1280×720	3600	0~3s

During the experimental process, the VFD started the centrifugal pump to reach the Q_s required by the experiment. When the Q_s reached a stable level, the mixer was used to blend the particles and carrier mixture evenly in the tank. The particles were then pumped into the pipeline with the carrier to initiate the slurry recycling in the tank and the pipeline. Considering the effect of the particles on the flow velocity, the VFD was adjusted slightly to modify the Q_s. When the flowmeter data and the pressure sensors remained stable, the flow pattern of the slurry was recorded for 10 s at a frequency of 1000 Hz.

2.4. Experimental Repeatability

The repeatability of this experiment was investigated to ensure the reliability of the results. The selected experimental parameters were random, and the flow velocity, particle diameter, and particle concentration were 4 m/s, 3 mm, and 5%, respectively. The experiment was repeated three times, and the results are shown in figure 5. It can be concluded from the results that the experiments are repeatable and the results are reliable.

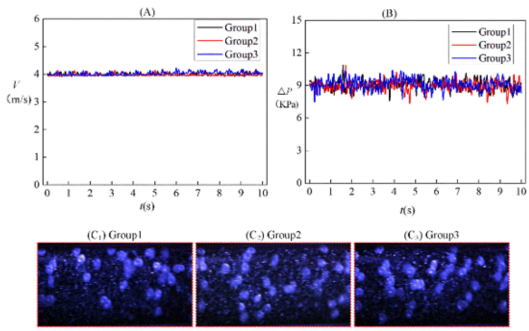

Figure 5. Experiment repeatability.

3. Experimental Results

The particle distribution over the cross-section of a horizontal pipe is often described in terms of the flow pattern. The flow pattern of the slurry is a crucial factor affecting the cleaning results. This section is divided into three parts to demonstrate the experimental results, while the effect of the flow velocity, particle concentration, and particle size on the flow pattern and pressure drop are analyzed.

3.1. The Effect of Flow Velocity

In this section, the slurry composed of φ3 mm particles and water was used to investigate the influence of the flow velocity on the flow pattern and pressure drop. The mass fraction was 5%, and the flow velocity range was 1 m/s-5 m/s, while the flow velocity was increased by 0.5 m/s for the experiment.

(1) Flow pattern

Determining the flow pattern is exceedingly complicated since the behavior of the slurry depends heavily on the competition between buoyancy, weight, and the hydrodynamic forces acting on the particles. The flow pattern is a critical factor affecting the cleaning results. Newitt and Richardson [23, 29] divided the flow pattern into four regimes: (1) Flow with a stationary bed or flow with a moving bed and saltation (with or without suspension and transferred via continuous or sporadic inter-granular contacts). (2) A heterogeneous mixture with some particles is presented in a bed, while others are supported by fluid turbulence. (3) Pseudo-homogeneous flow patterns at extremely high Q_s, where solids may approach an even distribution. (4) Homogeneous mixtures with suspended solids. Based on the flow velocity range in this paper, the flow pattern in the experiment can be divided into moving bed, heterogeneous, pseudo-homogeneous, and homogeneous mixtures, as shown in figure 6.

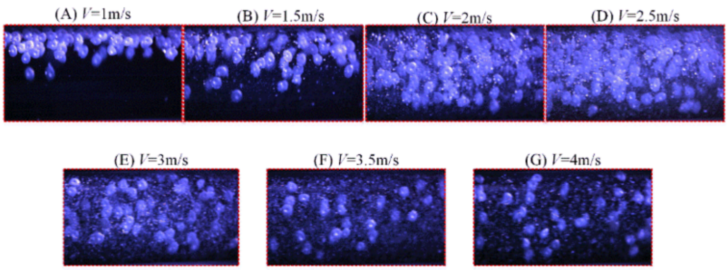

Figure 6. The flow pattern of the slurry.

At a flow velocity of 1 m/s, most of the particles accumulated at the top of the pipeline to form the moving bed since the density of the particles was lower than the water. As the flow velocity increased, the hydrodynamic forces became stronger, reducing the level of particle accumulation, allowing some of the particles to move to the bottom. The flow regime changed to a heterogeneous mixture. When the flow velocity reached 3 m/s, the flow regime became pseudo-homogeneous, reaching a homogenous state with a further increase in the flow velocity. These results are consistent with those obtained by Edelin and Denis [28].

(2) Pressure drop

Hydraulic gradients represent the pressure drop in the slurry and pure water under different flow velocities obtained during the experiment (see Eq. (4)) [12]:

$$I = \frac{\Delta P}{\rho_s g l} \tag{4}$$

where I represents the hydraulic gradients, ΔP denotes the measured static pressure drop, l is the distance between the two pressure sensors, and ρ_s signifies the specific mass of the slurry (see Eq. (5)):

$$\rho_s = \frac{\rho_p \rho_w}{(1 - C_m)\rho_p + C_m \rho_w} \tag{5}$$

where ρ_p is the density of the particles, ρ_w denotes the density of the water, and C_m is the mass fraction of the slurry particles. The hydraulic gradients of the slurry and pure water are shown in figure 7.

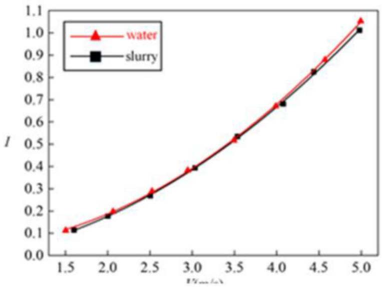

Figure 7. The hydraulic gradients of the slurry and pure water.

The hydraulic gradients of the slurry exhibited a significant increase in conjunction with a higher flow velocity. However, under the same flow velocity, the hydraulic gradient of the slurry was exceedingly close to that of pure water, indicating that the pressure drop does not differ significantly from that of pure water at a mass fraction of 5%.

3.2. The Effect of Particle Concentration

The results in Section 3.1 showed that the particles accumulated at the top of the pipe at low flow velocities and that the flow velocity must reach 3 m/s to achieve the pseudo-homogenous flow regime. An increase in the flow velocity substantially increased the pressure drop, placing a greater demand on the cleaning equipment. This section examines the influence of the particle concentration on the flow pattern at a flow velocity of 1 m/s-3 m/s. The slurry consisting ofφ3mm particles and three different mass fractions of 10%, 15%, and 20% were selected for the experiment. The flow patterns of different slurry concentrations at low flow velocities are shown in figure 8.

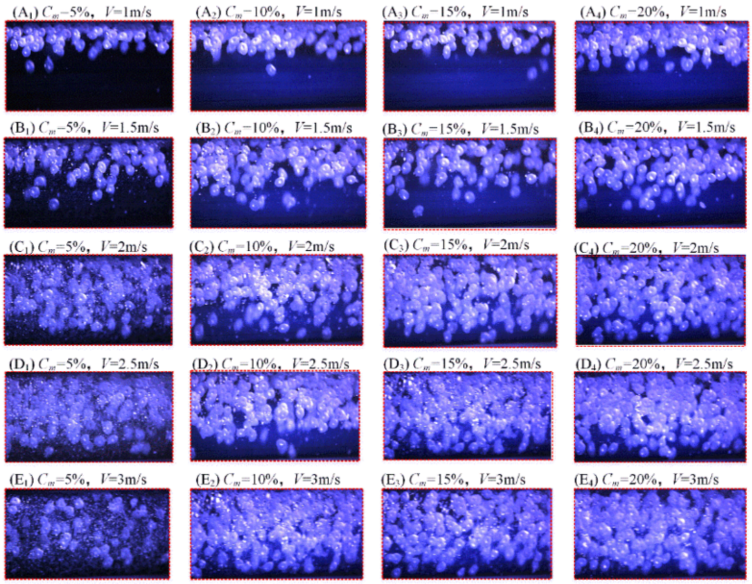

Figure 8. The flow patterns of different concentration slurry at low flow velocities.

At a flow velocity of 1 m/s, all four slurry concentrations displayed a moving bed flow pattern. Increasing the flow velocity reduced the accumulation level, changing the flow pattern. Furthermore, increasing the particle concentration at the same flow velocity could cause more particles to move to the bottom of the pipe (see figure 8(B)). When the flow velocity rose to 2 m/s, the 20% slurry particle concentration reached a pseudo-homogeneous level (see figure 8(C)). An increase in flow velocity to 2.5 m/s in the 15% slurry particle concentration also caused it to reach a pseudo-homogeneous state (see figure 8(D)). However, the 15% and 10% slurry particle concentrations did not display a pseudo-homogeneous state until the flow velocity reached 3 m/s (see figure 8(E)).

The slurry particle concentration influences the pressure drop behavior. Typical solid-liquid mixtures, such as coal, ash, or sand, as well as the wood chip forest biomass, present an increasing pressure drop in conjunction with increasing solid concentrations. However, Mahdi Vaezi found a slurry composed of 6.4 mm wheat straw fibers that showed a decreasing trend, producing lower fraction losses than the carrier fluid flow alone [23]. This section analyzes the impact of the particle concentration on the pressure drop of the slurry used in the experiment. In addition to reasonably selecting the cleaning equipment, this paper also investigates the energy consumption during the slurry operation. A modification to the earlier definitions by Wilson et al [30], Pullum, and McCarthy [31] is shown as:

$$SEC = \frac{\Delta P/l}{C_m \rho_p} \times 1000 \tag{6}$$

The pressure drop and specific energy consumption (*SEC*) are plotted against the superficial pipe velocity at various solid concentrations, as shown in figure 9.

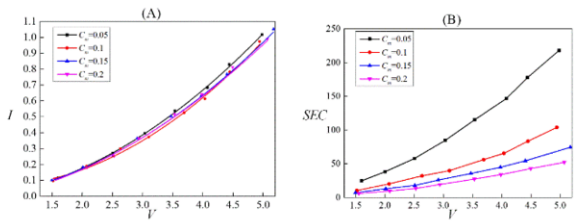

Figure 9. The pressure loss and specification energy consumption (*SEC*), plotted against the pipe superficial velocity at various solids concentration.

Figure 9(A) indicates that the drop in pressure in the four slurry particle concentrations shows no significant differences at the same flow velocity. Considering the pressure fluctuations and measurement errors, it can be concluded that when the particle concentration of the slurry is no more than 20%, the slurry concentration has no significant effect on the pressure drop at the same flow velocity. Figure 9(B) shows that increase the flow velocity will lead the *SEC* of the slurry during operation, and at the same flow velocity, *SEC* of the slurry will reduce with the particle concentration. Figure 8 and figure 9 show that the particles are distributed evenly when the particle concentration increases. However, when the particle concentration is below 20%, the pressure drop exhibited no significant increase, and *SEC* was reduced.

3.3. The Effect of Particle Size

When using the slurry composed of polypropylene-particles for pipeline cleaning, the particle size is a vital factor affecting the flow pattern and the cleaning results. Understanding how particle size impacts the flow pattern and pressure drop of the slurry helps to modify the particle preparation processes and optimize the design and operation of cleaning facilities. In this section φ0.6 mm and φ3 mm particles are selected for the experiment to investigate the effect of particle size on the flow pattern at the same concentration. The flow velocity did not exceed 2 m/s. The results are shown in figure 10.

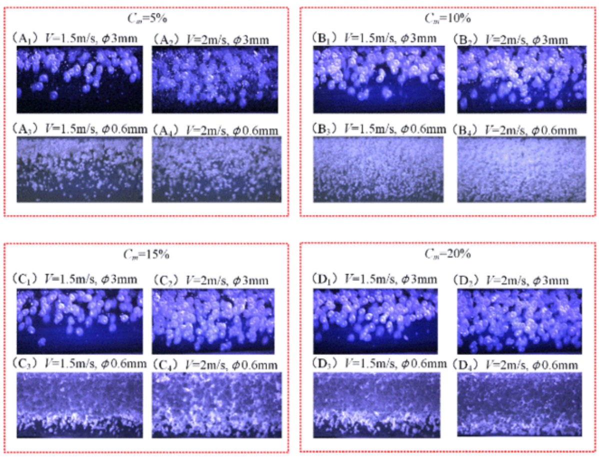

Figure 10. The flow pattern of different slurry.

When using φ0.6 mm particles, the slurry with a particle concentration of 5% reached a heterogeneous mixture at a flow velocity of 1.5 m/s. However, the flow regime of the other three slurry particle concentrations remained pseudo-homogeneous. When the flow velocity reached 2 m/s, the slurry with a particle concentration of 5% also reached a pseudo-homogeneous level. This indicated that higher concentrations allowed the particles to distribute more evenly in the pipeline, showing a similar trend to the φ3 mm particles. At the same flow velocity, the φ0.6 mm particles mix more evenly with water than the φ3 mm particles. Combining with the results in Section 3.2 the V_C which can make the slurry reach pseudo-homogeneous mixture of different type slurry are obtained in table 4.

Table 4. V_C of different type slurry.

	0.05	0.1	0.15	0.2
φ3mm	3m/s	3m/s	2.5m/s	2m/s
φ0.6mm	2m/s	1.5m/s	1.5m/s	1.5m/s

Figure 11 shows the drop in pressure of different types of slurries according to the experiment results. Considering the pressure fluctuations and measurement errors, it can be concluded that the particle size has no significant effect on the pressure drop at the same flow velocity and particle concentration.

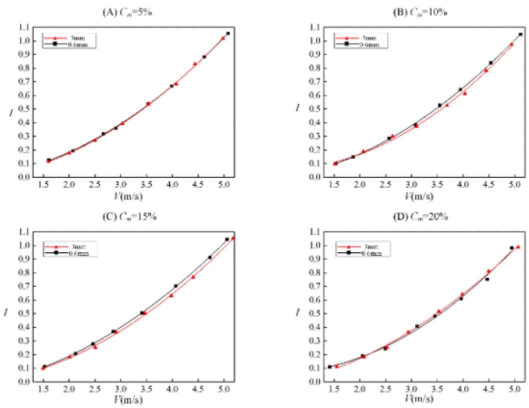

Figure 11. Pressure drop of different type slurry.

The slurry must reach a pseudo-homogeneous level to acquire satisfactory cleaning results. Therefore, the flow velocity must reach V_C. However, a higher velocity may lead to excessive ε_C, which is defined as the power to suspend solids in a pipe on a per unit mass basis (see Eq. (7))[17]:

$$\varepsilon_C = \frac{\Delta PQ}{C_m \rho_p l \left(\frac{1}{4}\pi D^2\right)} = SEC \times V_C \tag{7}$$

Q_s represents the flow rate. The ε_C of different types of slurries are shown in figure 12. According to the results shown in figure 12, the ε_C of the φ0.6 mm particles was lower than the $\varphi 3$ mm particles, while an increase in the particle concentration can effectively reduce ε_C.

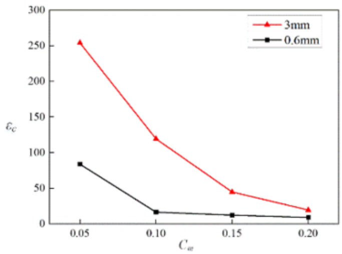

Figure 12. The ε_C of different parameter slurry.

4. Conclusion

In this paper, the slurry flow inside a horizontal pipe is visualized while measuring the drop in pressure due to the flow velocity, particle concentration, and particle size. Polypropylene particles of different sizes are used. Conclusions can be drawn as follows:

(1) The particles accumulate at the top of the pipe at a low flow velocity. The particles mix evenly with the water in the pipe at $V>V_C$. At a specific particle size, an increase in the particle concentration results in a lower V_C.

(2) At a specific particle size and concentration, an increase in the flow velocity causes a more significant pressure drop in the slurry. When the particle concentration does not exceed 20%, it has no significant influence on the pressure drop at the same flow velocity. However, an increase in the particle concentration results in a lower *SEC*.

(3) At a specific particle concentration, small particles can lead to lower V_C and ε_C. In addition, at the same flow velocity, the particle size has no significant influence on the pressure drop.

Acknowledgments

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Nomenclature

Symbol	Description	Unit
C_m	mass fraction	
D	internal diameter of pipe	mm
I	hydraulic gradients	
L	The length of the test loop	m
l	Distance between two pressure sensors	m

m	mass	kg
P	Pressure	KPa
Q	flowrate	m^3/s
S	area	m^2
V	flowmeter	m/s
V_w	the volume of the water	m^3
ε	the power to suspend solids in a pipe on per unit mass basis	W/kg
ρ	density	kg/m^3
Φ	Particle diameter	mm
SEC	specification energy consumption	W/kg.m

Subscript	Denotation
C	critical
m	mass
p	particle
s	slurry
w	water
△	the difference of the pressure
1,2	pressure sensor number

Reference

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