

Experimental investigation of flow characteristics of high-concentration ice slurry in pipes considering melting effects

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ABSTRACT

High-concentration ice slurry with phase change can be used as a pipe cleaning material, producing pollution-free effluents. The required characteristics of such slurry should be determined carefully before any cleaning process to slow down its melting rate and reduce cleaning costs. Excessive pump power should be avoided to minimize energy consumption, as well as high pressure on the pipeline wall to prevent pipe breakage. In this study, the flow and melting of high-concentration ice slurry were experimentally investigated in a closed-loop pipe system to examine the impact of key parameters on ice pigging. Results show that ice slurry exhibits effective cleaning performance during steady flow. The melting at the front of the slurry appears more pronounced due to the significant temperature difference between its front and the pipe wall, as well as the large heat exchange at the interface between the slurry front and the surrounding water. The melting rate of the ice slurry increases with flow acceleration, and the flowing distance increases with the slurry injection length, concentration, and flow velocity. The wall shear stress exerted by the ice slurry also increases with these parameters, and its rate of change is closely related to the velocity gradient near the boundary layer. A novel predictive formulation was developed to estimate the ice slurry flowing distance, featuring high accuracy and low experimental data requirements, by combining a physical modelling approach with a Gradient Boosting Regressor process. This research provides important information for the practical application of ice slurry in cleaning operations.

1. Introduction

Because of its high latent heat capacity (334 kJ/kg), ice slurry has become a promising medium for heat storage and transfer in various industrial applications, including food processing, district cooling, mining cooling, medical applications, secondary refrigerant of air conditioning, artificial snow production, and firefighting [1–3]. In addition, its enhanced mechanical cleaning effects make it particularly suitable for pipeline maintenance, where ice particles can effectively scour pipe walls and dislodge biofilms and deposits without the requirement for aggressive chemicals [4]. Fig. 1 shows an example of ice slurry with high concentration in a storage tank, and Fig. 2 shows an example of thick ice slurry being used for cleaning underground pipes, along with bottled samples collected during the cleaning.

The need for pipe and pipeline cleaning is well established, as impurities inevitably accumulate on their inner walls during prolonged operation, affecting the purity of the flowing fluids, increasing flowing

resistance and reducing their service life [5]. Regular pipe cleaning is therefore important for fluid quality and pipe preservation. Traditional cleaning methods mainly include chemical [6,7] and physical approaches. Common chemical methods include acid and alkali-based, which are often adopted together. Such methods may corrode the pipe and pollute the environment after long-term use. Physical cleaning methods, however, make use of physical force to clean pipe walls, usually through high-pressure water jet washing, pigging, gas-water pulse cleaning, and manual cleaning. This approach is not always suitable for pipes and pipelines with different topologies and may require large quantities of water [8–11]. To address these challenges, ice slurry cleaning has emerged as an innovative and energy-conscious alternative. In addition to removing internal deposits, ice slurry enables thermal energy recovery during the cleaning process, offering a more sustainable solution for modern energy systems.

A considerable number of studies have primarily focused on the pressure drop and heat transfer characteristics of low-concentration ice slurry. Mokrani et al. [12] experimentally demonstrated that the heat

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Nomenclature

σ	Standard uncertainty
X_i	Measurement value
$\overline{X}$	Average value
D_{in}	Internal diameter, mm
f	Darcy friction factor
T_a	Ambient temperature, °C
T_{fd}	Fluid temperature, °C
Q	Flow rate, m ³ /h
T_s	Temperature at the first sensor, °C
T_m	Temperature at the second sensor, °C
V	Volume, m ³
v	Flow velocity, m/s
v_0	Initial flow velocity, m/s
v_1	Final flow velocity, m/s
t_n	Time point related to temperature, s
L_f	Instantaneous flowing distance, m
L_{fm}	Flowing distance at full melting, m
l	Injection length of ice slurry, m
L_{res}	Residual slurry length, m
L_T	Total length of pipeline system, m
P	Power, W

ϕ	Volume fraction, %
ϕ_{con}	Constant volume fraction, %
ρ	Density, kg/m ³
μ	Dynamic viscosity, Pa·s
Re	Reynolds number
τ	Wall shear stress, Pa

Subscripts

a	Ambient
con	Constant
fd	Fluid
f	Flow
fm	Full melting
in	Internal
is	Ice slurry
ML	Machine Learning
n	Natural number
s	First temperature sensor location
m	Second temperature sensor location
r	Relative
res	Residual
T	Total
w	Water

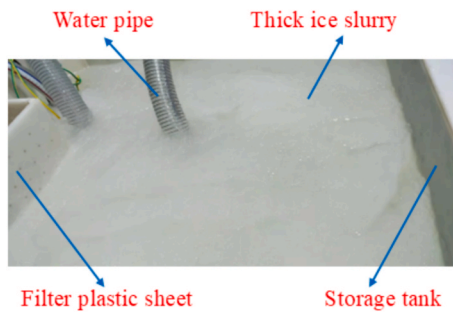


Fig. 1. Thick ice slurry in a storage tank.

transfer of ice slurry in chaotic coils is 28 % higher than in helical coils under low Reynolds number conditions, indicating that chaotic coils are more suitable for ice slurry flow. Bellas et al. [13] experimentally investigated the heat transfer and pressure drop characteristics of low-concentration ice slurry (5–20 % ice fraction) flowing through a plate heat exchanger. The results show that the pressure drop increases with flow rate and ice fraction, and the heat transfer capacity of ice slurry flow increases by more than 30 % compared to a single-phase flow. Egolf et al. [14] reported that in a horizontal pipe flow, the heat transfer coefficient of ice slurry rises with both ice fraction and Reynolds number when the ice concentration is kept under 30 %. Bedecarrats et al. [15] established the heat transfer and flow behavior of ice slurry flowing in a

corrugated tube heat exchanger and concluded that, under laminar flow, ice fraction plays a dominant role in enhancing the heat transfer coefficient, provided the ice fraction remains below 30 %. Fernandez-Seara et al. [16] carried out an experimental analysis on pressure drop and heat transfer of ice slurry flowing in a terminal fan-coil unit. The results established that pressure drop increases with flow rate, ice fraction, and Reynolds number; pressure drop for ice slurry is greater than for water and ethylene glycol solution; and the cooling capacity of the fan coil using ice slurry exceeds that of chilled water by a factor of 3.7–4.9. Mi et al. [17] experimentally studied the pressure drop and heat transfer characteristics of ice slurry, ranging from 0–20 % mass fraction, flowing through a plate heat exchanger. The conclusions highlighted that both pressure drop and heat transfer coefficient increase with flow rate, while at lower ice fractions, their dependence on ice fraction is minimal. Suzuki et al. [18] numerically investigated the heat transfer characteristics of ice slurry flowing in a square duct. The authors found that the Nusselt number rises with both Reynolds number and ice fraction. Cai et al. [19] conducted a numerical investigation on the heat transfer of ice slurry under a pulsating flow and showed that pulsating flow significantly improves the heat transfer performance. Additionally, the heat transfer coefficient rises with higher pulsation frequency, greater velocity amplitude, larger ice crystal size, and higher ice fraction.

Although the above-cited literature provides valuable insights into the behavior of low-concentration ice slurry, they cannot be directly extended to high-concentration ice slurry due to increased complexity in flow dynamics and phase interactions. Currently, the research of high-concentration ice slurry remains relatively limited, particularly for



(a) On-site cleaning underground pipes



(b) Water quality samples ordered by cleaning time

Fig. 2. On-site cleaning of underground water mains.

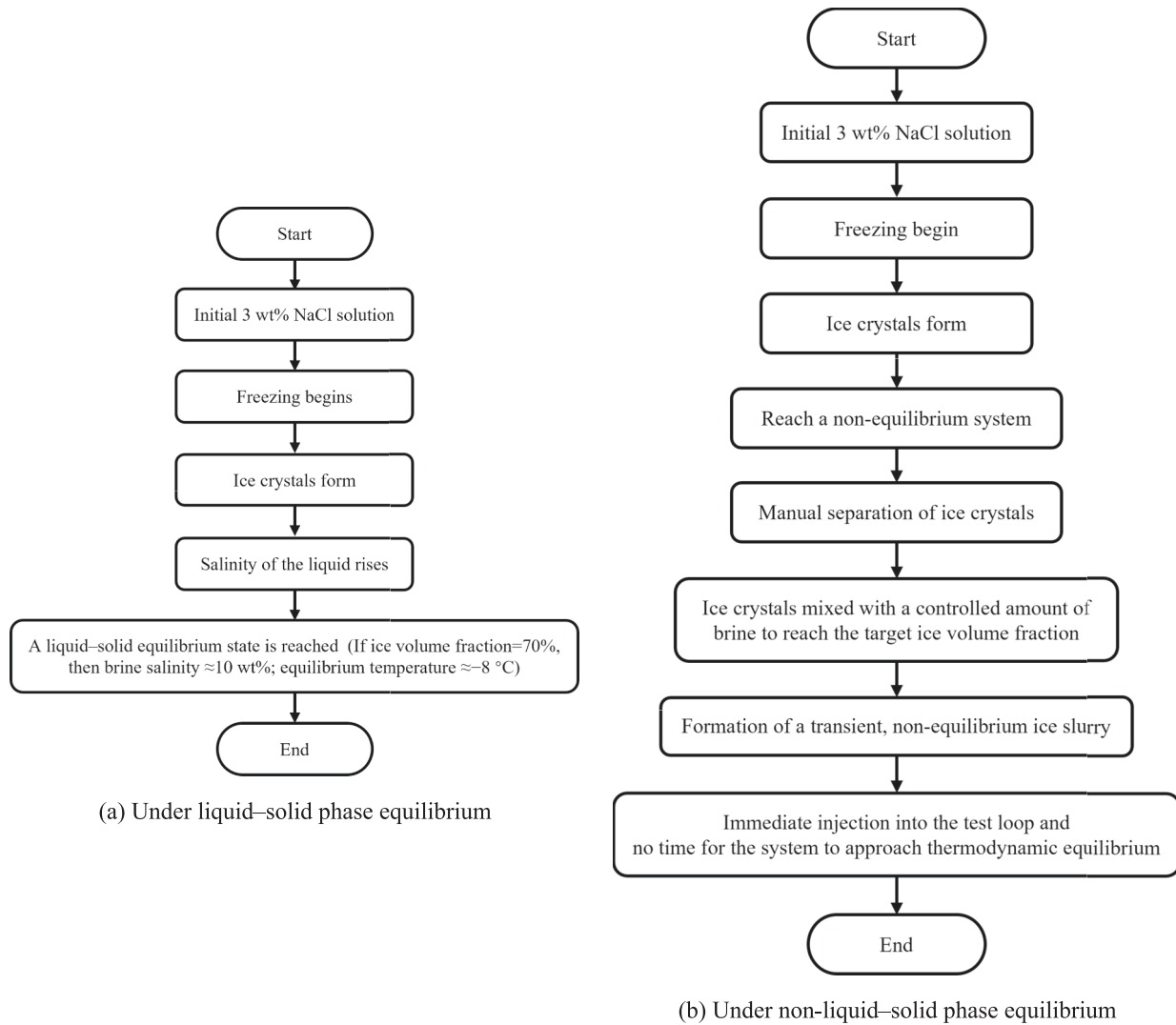


Fig. 3. Different ice slurry preparation processes.

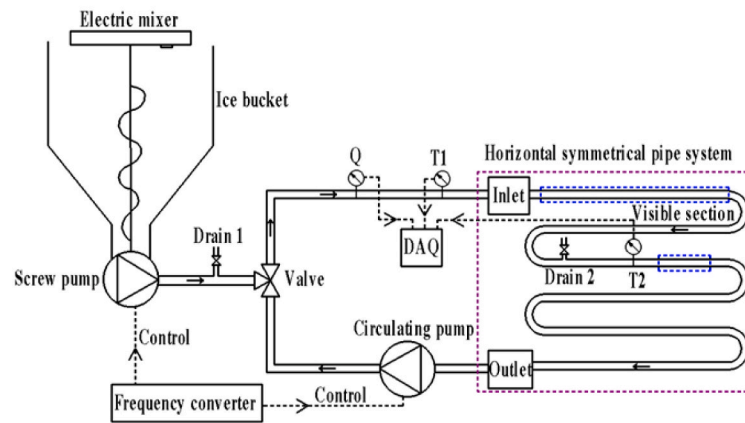
pipe cleaning. Quarini [20] patented a method for cleaning and separation using ice slurry in fluid flow conduits. In a subsequent study, Quarini [4] applied ice slurry to clean pipes with different shapes and found that high-concentration ice slurry is effective in removing soft fouling and pipe deposits, and ice slurry achieves better cleaning performance compared to ambient or hot water. Shire et al. [21] investigated the flow mixing characteristics of dense ice slurry in pipes and demonstrated its self-repairing capability, allowing it to remain cohesive under different flow regimes. In the same year, Shire et al. [22] applied ultrasound to monitor ice slurry concentration in a pipe, revealing its higher sound velocity and greater signal attenuation compared to other fluids due to its high bulk modulus. Subsequently, Shire et al. [23,24] examined the pressure drop of high-concentration ice slurry in different pipe configurations and heat exchangers, showing that its pressure drop exceeds that of water and grows with increasing ice content and flow velocity. Evans et al. [25] studied the flow and melting of thick ice slurry in a pipe and applied Shire's ultrasonic technique to track the real-time variation of ice volume fraction within the pipe. Quarini et al. [26] proposed an analytical approach grounded in transient solid heat transfer to estimate the thermal behavior and lifespan of ice slurry within a simple pipe, but it overlooked percolation effects. Hales et al. [27] employed a non-invasive electromagnetic method to assess thick ice slurry concentration within a pipe, showing that due to fundamental differences in atomic structure, electromagnetic waves are readily

absorbed by water but shows minimal attenuation in ice slurry. Hu and Tao [28] applied an Eulerian-Eulerian approach grounded in granular flow theory to simulate the isothermal flow of ice pigging. Their model considered an ice volume fraction of only 40 %, falling short of the typical range in real-world cleaning processes, and omitted both melting and thermal exchange phenomena. For the model to be more realistic, Hu et al. [29] later incorporated a phase-change model to capture the behavior of flow and melting during ice pigging. Despite these advancements, the model still assumed a constant wall temperature, potentially limiting its applicability in thermally dynamic environments.

The above literature reveals that investigations into high-concentration ice slurry are still limited in scope and depth, suggesting the need for more comprehensive exploration. The objective of this study is to investigate the relationship between the amount of ice slurry and the corresponding pipe length to be cleaned. The key novelty of this work lies in the following aspects: (i) the temporal evolution characteristics of flow patterns during the ice slurry cleaning process are described; (ii) the mechanism of ice slurry cleaning is analyzed by combining flowing distance and mechanical characteristics; (iii) a novel predictive formula is established between the slurry flowing distance and the initial injected length, concentration and velocity, based on physical and machine learning methods. The outcome of this research can fill the gap within experimental studies of high-concentration ice slurry, provide a reference for ice slurry pigging in actual engineering



(a) Experimental rig setting: 1. Ice bucket, 2. Screw pump, 3. Three-way valve, 4. Electromagnetic flowmeter, 5. First temperature sensor, 6. Second temperature sensor, 7. Pipe circulating pump, 8. Frequency converter, 9. Water draining device, 10. Air exhausting device, 11. Transparent hose, 12. Transparent plastic pipe, 13. Horizontal symmetrical stainless-steel pipes, 14. DAQ (Data acquisition system), 15. Water discharge bucket



(b) Schematic of the experimental rig. The blue dashed boxes represent the visualization sections

Fig. 4. Experimental testing apparatus [44].

applications, and help control pipe cleaning costs in various industries.

2. Experimental settings

2.1. Ice slurry production

The scraping method [30] was applied here to generate ice slurry. Salt was selected as the freezing point depressant, with a mass fraction around 3 % of the aqueous solution, before generating the slurry. Different from the monodisperse sphere with uniform size, the ice slurry is a polydisperse system that contains particles of varying shapes and sizes [31]. In most cases, the shapes of ice particles in the ice slurry are irregular, hence typically not perfect spheres or cubes, and may have jagged edges and/or sharp points. This happens because ice slurries are often produced through freezing water in conditions that promote rapid formation of tiny ice crystals, which do not have time to form uniform shapes. Ice slurries can form ice particles with a flake-like appearance, especially in industrial applications like cooling systems, which are usually thin and somewhat flat but still irregular. In certain conditions, particularly when freezing occurs under specific supercooling

conditions, ice particles can form needle-like crystals, which are slender and elongated. The size of ice particles in the ice slurry ranges from a few micrometers to several millimeters and the overall size distribution typically depends on the method of ice production. In this study, the average size of the ice crystals used was approximately 0.05 mm, with most particles falling within the range of 0.01–0.1 mm, as determined by microscopic observations. The ice crystal size distribution obtained in this work was consistent with that reported in the literature [32,33].

2.2. Concentration measurement

The coffee press method (pressure method) was considered to measure the concentration (volume fraction) of ice slurry [30]. This method involves placing a certain volume of ice slurry (V) into a sealed coffee press, then applying pressure to expel the water from the slurry. The remaining volume is considered the volume of ice particles (V') and the ice fraction (ϕ) of ice slurry is calculated from Eq. (1). The operation of the coffee press method is relatively simple, and the measurement results can be obtained quickly. It is suitable for ice slurries with different concentration ranges and can be measured under a wide range of



(a) First temperature sensor



(b) Second temperature sensor

Fig. 5. Locations of the two temperature sensors.

experimental conditions.

$$\phi = \frac{V}{V} \quad (1)$$

For a monodisperse system, the densest packing of equally sized spheres is about 74 %, but a polydisperse system will tend to increase the maximum packing factor. Previous investigations on ice slurry have indicated that ice crystals exhibit a more prolate crystal shape, such as ellipsoids [34] with a maximum packing fraction of 76 % [35] or spherocylinders [36] with a maximum packing fraction of 91 % [37]. The ice slurry concentration considered in this work was higher than 65 %.

It should be highlighted that the ice volume fraction in the present experiments was determined and injected into the test loop in a non-liquid-solid equilibrium state. Fig. 3 illustrates two different ice slurry preparation processes. The flowchart corresponding to Fig. 3 (b) was adopted in this study. First, a large amount of ice slurry was produced in a single batch by an ice maker, noting that when the ice maker stopped operating, the ice slurry in the storage tank was not in a state of liquid-solid phase equilibrium. The ice crystals were then manually separated from the storage tank and mixed with a controlled amount of brine to reach the target ice volume fraction. The reconfigured ice slurry therefore remained in a transient, non-equilibrium state. Finally, the ice slurry with the adjusted concentration was immediately injected into the pipeline loop, leaving no time for the system to approach thermodynamic equilibrium. As the purpose of ice production was only to obtain high-concentration ice slurry, there was no need for the resulting ice slurry to reach an equilibrium state. Hence, for the reconfigured ice slurry used in the present experiments, the liquid-phase salinity was not equal to the equilibrium salinity, the ice fraction represented only an apparent volume fraction, and the temperature measured by the sensors in the pipeline did not correspond to the equilibrium temperature; more precisely, it was higher than the equilibrium temperature [25].

2.3. Experimental apparatus

Fig. 4 (a) shows the apparatus used to carry out the experiments presented here, along with the associated process system, which can be divided into two parts. The first part is the ice slurry injection section, and the second one is the closed pipe loop in which the ice slurry circulates. The ice slurry injection section is mainly composed of an injection bucket mounted above a screw pump. The closed pipe loop mainly consists of an electromagnetic flowmeter, two temperature sensors, a driving pump (piping circulating pump), a frequency converter, an air exhausting device, a water draining device, a three-way valve, three transparent hoses, two small sections of transparent plastic pipes, and a horizontal symmetrical stainless-steel piping system. The frequency converter is used to adjust the power of the screw pump and circulating pump, and the temperature sensors are used to monitor the actual temperature of the fluids, while the electromagnetic flowmeter is

Table 1
Detailed information of the experimental instruments.

Instruments	Types	Measuring range	Uncertainty	Specification
Screw Pump	G25-1	0 – 5 m ³ /h	/	Inlet: DN50; Outlet: DN40; Power: 0 – 2.2 KW; Head: 0 – 60 m
Piping Circulating Pump	IHG50-200IB	0 – 21.6 m ³ /h	/	Inlet and outlet: DN50; Input: 380 V; Power: 0 – 5.5 KW; Head: 0 – 37 m
Frequency Converter	/	0 – 50 Hz	/	Input: 380 V; Power: 0–5.5 KW
Electromagnetic Flowmeter	LDG-SUP-DN50	3.5 – 20 m ³ /h	0.5 %	Input: 220 V; Output: 4 – 20 mA
Temperature Sensors	BDR-A187A	–50 ~ 100 °C	0.2 %	Input: DC 24 V; Output: 4 – 20 mA
Data Acquisition Card	NI USB-6343	32 AI (16-Bit)	0.01 %	Output: –10 ~ 10 V

used to get the actual flowrate of the pipe system. The transparent plastic pipes can provide visuals on the actual flowing and melting state of the ice slurry. Fig. 4 (b) provides a concise schematic of the apparatus.

The total perimeter of the closed pipe loop is approximately 78.6 m. This closed pipe loop allows the ice slurry to flow for very long distances until it melts fully, avoiding the use of a long pipe system. The nominal diameter of the pipes is 50 mm, which is frequently used in practical engineering projects. The water draining device, highlighted as Number 9 in Fig. 4 (a), is located at the top of the entire unit. Its function is to drain away water and to capture and extract any air present in the pipe system. The first and second temperature sensors shown in Fig. 5, located at 2 and 39.3 m (half the total perimeter) far from the three-way valve, respectively, provide the temperature of the fluids (ice slurry and water) flowing in the system. Information regarding the experimental instruments is provided in Table 1.

2.4. Experimental procedure

Before starting the testing, the closed pipe loop was filled with water, and any air still present in the system was removed via the air exhausting device. The ice slurry injection process could then begin by switching on the three-way valve. Ice slurry with the required concentration was poured into an ice bucket first and agitated with an electric mixer until it became uniform. The water-draining valve of the closed pipe loop was then opened and the screw pump activated to transport the ice slurry into the closed pipe loop. Note that the electric mixer kept stirring the ice slurry in the bucket to maintain its homogeneity during the whole injection process. When the injection of ice slurry was complete, the

Table 2
Uncertainties from measurement.

Measured parameters	Mean value	Standard Uncertainty (68 %)	Expanded Uncertainty (95 %)
Volume fraction of ice particles, ϕ (%)	65 %	± 0.047 %	± 0.106 %
Ambient temperature, T_a (°C)	25°C	± 0.042 °C	± 0.096 °C
Internal diameter, D_{in} (mm)	50.02 mm	± 0.0416 mm	± 0.094 mm
Injection length of ice slurry, l (m)	10.46 m	± 0.034 m	± 0.077 m
Flow rate, Q (m ³ /h)	6.984 m ³ /h	± 0.016 m ³ /h	± 0.036 m ³ /h
Fluid temperature, T_{fd} (°C)	20.04 °C	± 0.045 °C	± 0.103 °C

three-way valve was switched to the closed pipe loop, the water-draining valve was stopped, the data acquisition system was started, and the piping circulating pump was activated. Flow rates and temperatures were constantly monitored and collected in real time via the data acquisition system during the whole duration of the experiments. A clock-triggered, single-point sampling method was employed for data acquisition. The sampling frequency was 10 Hz, and the total sampling duration was 900 s, resulting in 9,000 samples collected per channel in each experimental run. Data were instantaneous values in this experiment, and signal isolators were employed to suppress the interference during data acquisition. Each isolator accepted a 4–20 mA current input

and provided a 0–5 V voltage output, thereby eliminating the need for additional load resistors to convert the current signals into the voltage signals before acquisition by the NI DAQ card.

2.5. Experimental uncertainties

The ice slurry concentration before injection, the ambient temperature, the hydraulic diameter, and the flow rates and temperatures of fluids (ice slurry and water) in the closed pipe were measured. The measurement uncertainties of the instruments could be obtained [38]. To ensure the repeatability of the experimental data, each parameter was directly measured more than 20 times. For the accuracy of data calculation, the maximum and minimum values in each set of measurement data were removed. Based on the standard deviation formula provided by Eq. (2), the standard uncertainty of each parameter being measured could be established, see in Table 2. As can be seen, the standard uncertainty values of all measured parameters generally do not exceed 0.1, which provides confidence in the accuracy of the measured data.

$$\sigma(X) = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n(n-1)}} \quad (2)$$

where $\sigma(X)$, X_i and $\bar{X}$ are the standard uncertainty, measurement value and average value, respectively.

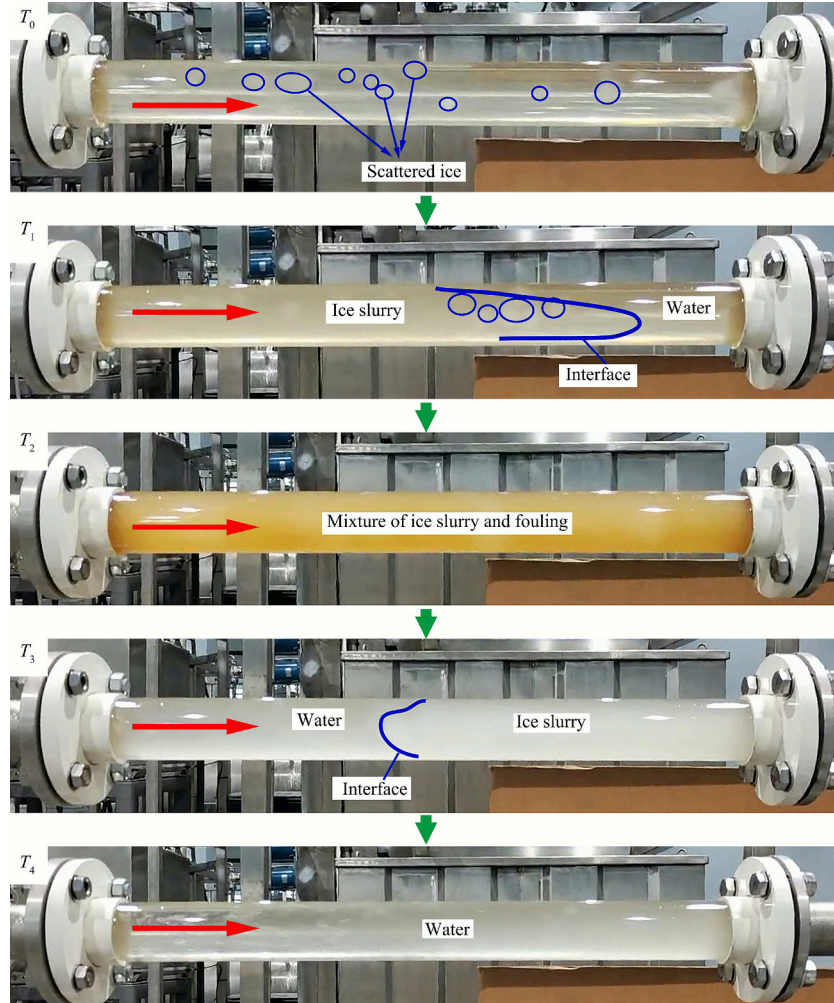


Fig. 6. Ice slurry pipe cleaning process.

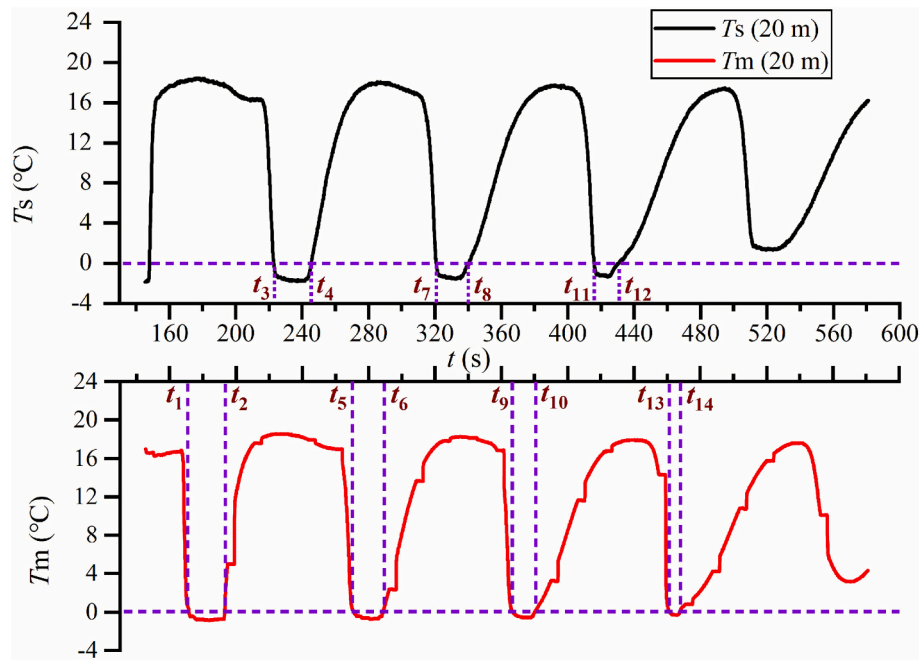


Fig. 7. Variation of fluid temperature over time. T_s and T_m refer to the measured temperature by the first (start, subscript s) and second (middle, subscript m) sensors, respectively; t_n ($n = 1, 2, 3, \dots$) are time sequences, and refer to the intersection points of the vertical dotted line and the X-axis.

3. Experimental results

3.1. Flow state of the ice slurry

Fig. 6 shows the pipe cleaning process. Although not highly apparent, the melting of the columnar ice slurry starts at its front. At Stage T_0 , some scattered clumps of floating ice particles are present due to buoyancy, when most of the ice slurry front has melted. These scattered clumps of ice particles, of size ranging from approximately 5 to 15 mm, have no longer any cleaning effect as the friction with the tube wall approaches zero. Stage T_1 shows the interface between the ice slurry front and water, which displays a finger-shaped structure, accompanied by scattered small ice aggregates. At Stage T_2 , a mixture of ice slurry and fouling can be seen. The yellow substance in the fouling is due to rust that forms on the inner surface of the pipe. With the flow of ice slurry, contaminants gradually accumulate, reaching a peak concentration before decreasing, until the slurry becomes completely clean, see Stage T_3 . An interface between the finger-shaped tail of the ice slurry and water is also visible in Stage T_3 . The ice slurry finally passes fully through the transparent section, see Stage T_4 .

Based on visual observations, the melting of the ice pig mainly occurs at its front, and its rear plays a key role in removing and collecting fouling. This is due to the large temperature difference between the front of the ice pig and the pipe wall, and the high heat exchange at the interface between the slurry front and the surrounding water. The slurry front lowers the temperature of both the pipe wall and the water ahead of the ice slurry, thereby reducing the melting rate at the rear of the ice slurry. In addition, the layer of ice slurry in contact with the tube wall also melts quickly. When this layer becomes a film of water, it reduces the heat transfer rate between the ice slurry and the wall due to the presence of a temperature gradient.

From the above analysis, it becomes evident that the relationships between the amount of ice slurry injected into the pipeline, the pollution degree, and the length of pipe to be cleaned, are key research points as they affect the rational use of energy. However, before discussing this problem, it is necessary to explore the flowing distance and melting of high-concentration ice slurry.

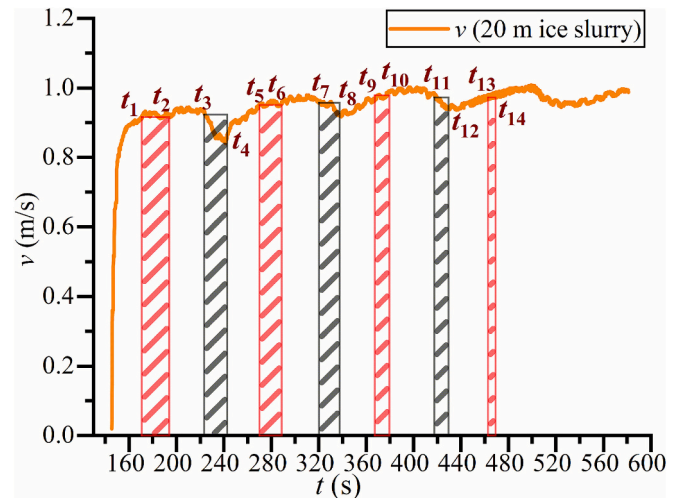


Fig. 8. Variation of fluid velocity over time. t_n are time sequences. The rectangular boxes represent the required time for the remaining ice slurry to pass through the sensors.

3.2. Factors influencing the ice slurry flowing distance

There are many factors that can affect the flowing distance of ice slurry in a pipeline, such as the pipe diameter, ambient temperature, slurry injection length, slurry injection concentration, slurry flow velocity, etc. In this work, the diameter of the pipeline is constant (50 mm), and the ambient temperature is 25 °C. The effects of slurry injection length, slurry injection concentration and slurry flow velocity on the flow distance were investigated.

3.2.1. Effects of injected ice slurry length

Fig. 7 shows the temperature variation of fluids (ice slurry and water) over time during the experiments. T_s and T_m refer to the measured temperature by the first (start, subscript s) and second (middle, subscript m) sensors, respectively. The dashed horizontal lines in the plots

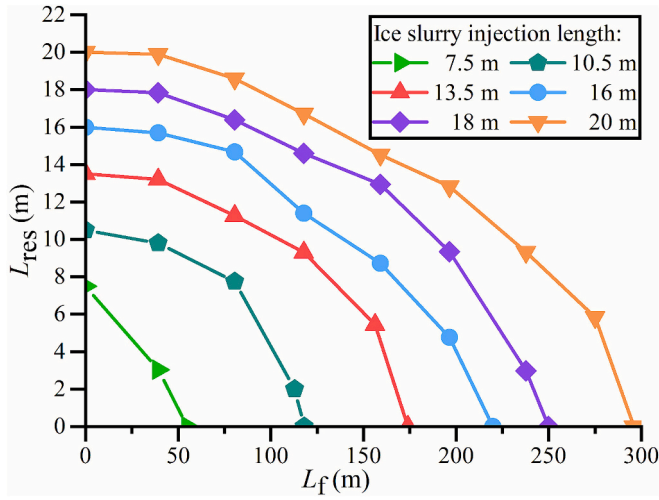


Fig. 9. Variation of residual ice slurry length with instantaneous flowing distance at different injection lengths. Note that error bars are not shown as they are smaller than the symbols size.

represents 0 °C. The temperature above those dashed lines therefore indicates that water is passing through the sensor while temperature below this line indicates that ice slurry is flowing through the sensor. Marking points, t_n ($n = 1, 2, 3, \dots$) are time sequences, they refer to the intersection points of the vertical dotted line and the X-axis, and the period between t_n and t_{n+1} ($n = 1, 3, 5, \dots$) represents the required time for the remaining ice slurry to pass through the sensors. Since the injection length of the ice slurry (70 % concentration, 1 m/s flow velocity) is relatively long at 20 m, the number of ice slurry circulation cycles in the closed-loop system increases accordingly.

Fig. 8 shows the variation of fluid velocity over time during the flow in the closed-loop system. As observed, the fluid velocity fluctuates slightly. This instability arises because the injected ice slurry (70 % concentration, 20 m in length) experiences variations in concentration when flowing, which are caused by buoyancy forces, inter-particle interactions, and local non-uniformities in heat transfer. As a result, the flow behavior remains unsteady throughout the process. Note that the meaning of t_n in Fig. 8 is identical as that in Fig. 7, and the rectangular boxes show the required time for the remaining ice slurry to pass through the sensors, expressed as $t_n - t_{n+1}$ ($n = 1, 3, 5, \dots$). The black rectangle denotes the period during which the residual ice slurry in the pipe passes through the first temperature sensor, while the red rectangle indicates the corresponding time for the second temperature sensor.

As the ice slurry melts in the pipe, the width of rectangular box is constantly decreasing until it reaches zero. Based on the required time for the remaining ice slurry to pass through the sensors as highlighted in Fig. 8, the length of the residual ice slurry L_{res} passing through the sensors can be obtained from time and velocity.

$$L_{res} = \int_{t_n}^{t_{n+1}} v dt, (n = 1, 3, 5, \dots) \quad (3)$$

where v is the flow velocity, and the time interval from t_n to t_{n+1} represents the duration during which the residual ice slurry flows past the temperature sensors.

Combining Fig. 7 and Fig. 8 with Eq. (3), the relationship between the residual ice slurry length (L_{res}) and the instantaneous flowing distance (L_f) of the ice slurry in the closed-loop system can be determined, which is shown in Fig. 9. As can be observed in this figure, the flowing distance of the ice slurry in the closed-loop system increases with the ice slurry injection length. Moreover, the slope of each curve is negative, indicating a decreasing residual ice slurry length with increasing flowing distance, while the absolute value of the slope increases with the flowing distance, suggesting that the melting rate of the ice slurry presents a

continuously increasing trend. Shire et al. [21] have reported that high-concentration ice slurry exhibits self-healing behavior during pipeline flow, suggesting that such slurry has the ability to maintain its structural integrity. Thus, during the initial stage of the flow, the melting rate of the ice slurry remains low despite the large temperature difference between the slurry and the tube wall. In addition, it should also be noted that the ice slurry in contact with the tube wall melts quickly due to the large temperature difference and then forms a layer of water film, which insulates the remaining ice particles from direct thermal contact with the tube wall, thereby reducing the heat transfer. As most of the ice slurry melts, the remaining ice particles come into greater contact with the water in the closed-loop system, thereby enhancing the thermal exchange and accelerating the melting rate.

The wall shear stress exerted by a high-concentration ice slurry is the direct cleaning force acting on the fouling layer of the pipe wall. For both theoretical modelling and experimental evaluation, the wall shear stress is widely recognized as a key parameter in quantifying the cleaning efficiency of slurry-based systems. A quantitative relationship between pump power and wall shear stress can be derived from fundamental fluid mechanics principles:

$$P = \tau \cdot v \cdot \pi \cdot D \cdot L \quad (4)$$

where P is the pump power, τ is the wall shear stress, v is the flow velocity, D is the pipe diameter, and L is the pipe length.

When the pump operates at a constant power under different ice slurry injection lengths, the following equation can be obtained.

$$\tau_{is} \cdot v_0 \cdot \pi \cdot D \cdot l + \tau_{w0} \cdot v_0 \cdot \pi \cdot D \cdot (L_T - l) = \tau_{w1} \cdot v_1 \cdot \pi \cdot D \cdot L_T \quad (5)$$

Rearranging Eq.(5) yields:

$$\tau_{is} = \frac{\tau_{w1} \cdot v_1 \cdot L_T - \tau_{w0} \cdot v_0 \cdot (L_T - l)}{v_0 \cdot l} \quad (6)$$

where τ_{is} is the wall shear stress of the ice slurry at the initial stage of the flow, τ_{w0} is the wall shear stress of the water at the initial stage, and τ_{w1} is the wall shear stress of the water at the final stage. v_0 denotes the initial flow velocity in the pipe, while v_1 represents the final flow velocity. L_T is the total length of the closed-loop system, and l is the injection length of ice slurry.

Among the variables in Eq.(6), only τ_{w0} and τ_{w1} need to be further calculated. Based on the flow velocity and the Darcy friction factor, the wall shear stress of water can be calculated:

$$\tau = \frac{f \rho v^2}{8} \quad (7)$$

where f , ρ , and v denote the Darcy friction factor, density, and flow velocity of water, respectively.

During the experiment, the flow velocity of water in the pipe was never lower than 0.5 m/s. Given the density and viscosity of water under ambient conditions, the corresponding Reynolds number, according to Eq.(8), was never lower than 25,000; this clearly falls within the range of a fully developed turbulent flow.

$$Re = \frac{\rho v D}{\mu} \quad (8)$$

where Re , D , and μ denote the Reynolds number, the pipe diameter, and the dynamic viscosity of water, respectively.

Thus, the Darcy friction factor for water can be determined:

$$f = 0.3164 \cdot Re^{-0.25} \quad (9)$$

The wall shear stress of the ice slurry at the onset of flow, corresponding to different injection lengths, was determined according to Eqs.(6)-(9), as shown in Fig. 10. The blue curve illustrates that the initial flow velocity of the ice slurry decreases as the injection length increases. With a fixed pump power, increasing the injection length of the ice

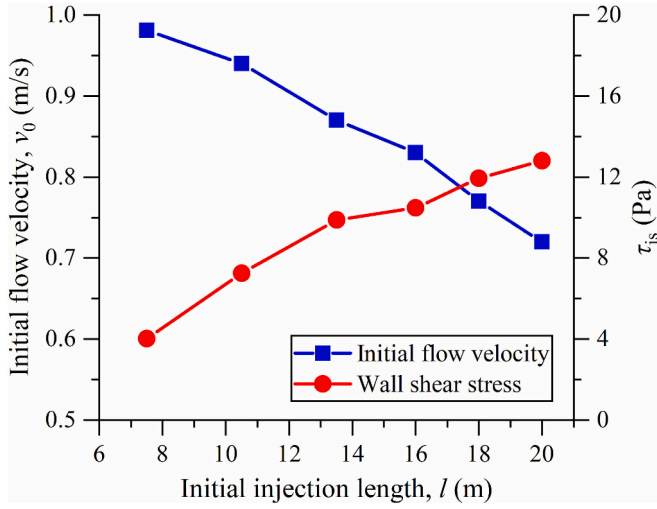


Fig. 10. Variation of initial flow velocity and wall shear stress of ice slurry with initial injection length. Note that error bars are not shown as they are smaller than the symbols size.

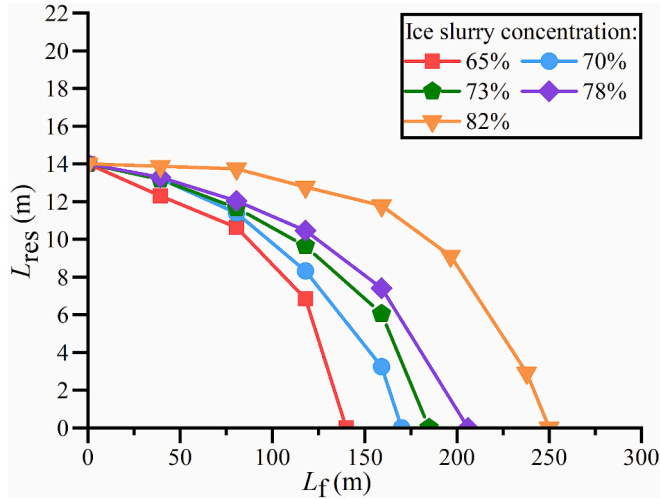


Fig. 11. Variation of residual ice slurry length with instantaneous flowing distance under different injection concentrations. Note that error bars are not shown as they are smaller than the symbols size.

slurry reduces the energy available per unit length, which weakens the pressure-driven force along the flow path, thereby decreasing the overall flow velocity.

Under the same pump power, an increase in the injection length enhances viscous resistance and flow friction in the pipe. This necessitates a greater velocity gradient and pressure drop per unit length, thereby resulting in a progressive increase in wall shear stress, as shown by the red curve. However, the rate of increase in wall shear stress gradually decreases with increasing ice slurry injection length. This phenomenon results from the combined influence of flow resistance and ice slurry viscosity. As the slurry travels over longer distances, its velocity decreases, leading to a reduced wall shear stress in the latter sections of the pipeline.

3.2.2. Effects due to concentration

Fig. 11 shows the relationship between the residual ice slurry length and the instantaneous flowing distance for different slurry injection concentrations, all with the same initial length (14 m) and a flow velocity of 1 m/s. It appears clearly that the flowing distance of the ice

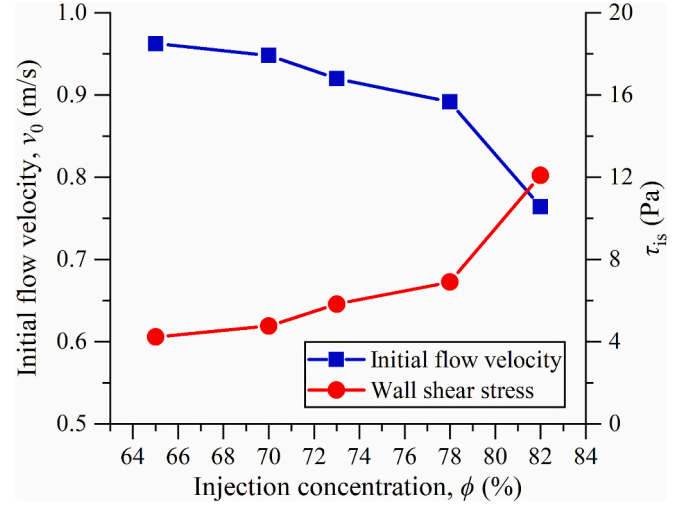


Fig. 12. Variation of initial flow velocity and wall shear stress of ice slurry with injection concentration. Note that error bars are not shown as they are smaller than the symbols size.

slurry in the closed-loop system increases with the slurry injection concentration, as a higher ice slurry concentration corresponds to a higher energy storage density. In addition, the increasing absolute value of slope of each curve with flowing distance indicates a continuous rise in the ice slurry melting rate during the ice slurry flow. It can also be observed from the figure that, at the initial stage of the ice slurry flow, the absolute slope of the curve corresponding to higher concentrations is smaller than that of lower concentrations. This indicates that, under identical thermal conditions, the initial melting rate of high concentration ice slurry is lower than that of low concentration slurry. This phenomenon can be attributed to the higher energy storage density of high-concentration ice slurry. A higher concentration implies a larger proportion of ice particles, which requires more latent heat to initiate melting.

Fig. 12 shows the variation of the initial flow velocity and wall shear stress of the ice slurry under different slurry injection concentrations, carried out with the same pump power. As the concentration of ice slurry increases, the initial flow velocity tends to decrease. This is primarily due to the higher viscosity and flow resistance of high-concentration ice slurry, which leads to a lower initial flow velocity under the same driving force. Similarly, due to the higher viscosity and yield stress of the high-concentration ice slurry, the flow resistance near the pipe wall increases, resulting in higher wall shear stress. The increase in wall shear stress grows with increasing ice slurry concentration. An increase in ice slurry concentration means a higher content of ice particles, resulting in a significant rise in slurry viscosity. The higher viscosity increases the velocity gradient between fluid layers, thereby accelerating the growth of wall shear stress.

During the ice slurry cleaning process, the slurry concentration is a key parameter that determines its flow characteristics, shear capability, and cleaning efficiency. If the concentration is too low, the ice slurry may fail to remove pipe wall fouling effectively; if it is too high, the flowability of the ice slurry will be reduced. When the flowability of the ice slurry is poor, a greater driving force is required to maintain the same flow rate, resulting in increased energy consumption. In addition, reduced flowability may cause ice crystal aggregation, especially in low-flow or narrow pipeline sections, thereby increasing the risk of blockage. More critically, insufficient flowability can lead to decreased wall shear stress and weakened particle-wall interactions, ultimately reducing the scouring effect and compromising the overall cleaning performance. It has been observed during the experiments that the flowability of ice slurry deteriorates markedly when the concentration approaches 80 %. Therefore, an appropriate trade-off between concentration and

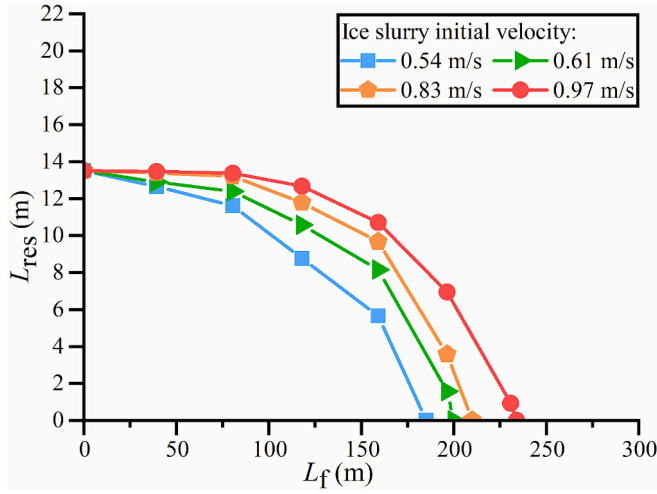


Fig. 13. Variation of residual ice slurry length with instantaneous flowing distance under different initial flow velocities. Note that error bars are not shown as they are smaller than the symbols size.

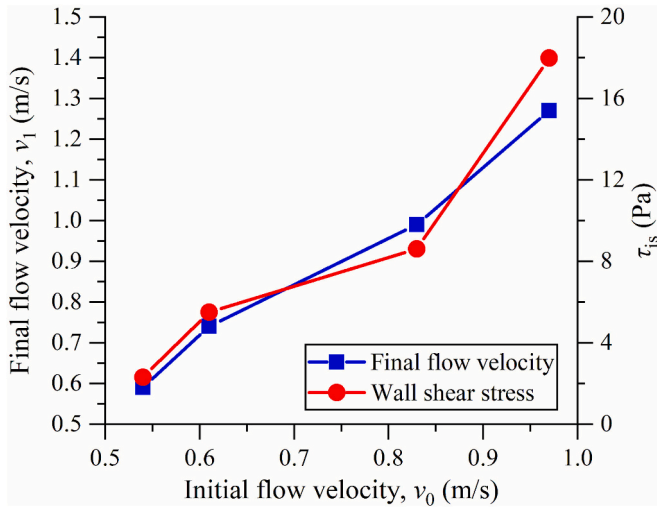


Fig. 14. Variation of wall shear stress and final pipe flow velocity with initial flow velocity. Note that error bars are not shown as they are smaller than the symbols size.

flowability must be considered to ensure high cleaning efficiency.

3.2.3. Effects due to the flow velocity

Fig. 13 shows the relationship between the residual ice slurry length and the instantaneous flowing distance for different initial flow velocities, but with the same slurry injection length (13.5 m) and concentration (70 %). It can be observed that the flowing distance of the ice slurry in the closed-loop system increases with the initial flow velocity. This is mainly because at higher flow velocities, the ice slurry has a shorter residence time in the pipe. As a result, the heat exchange between the slurry and the pipe wall is limited, reducing the amount of heat absorbed by the ice slurry. This slows down the melting process and allows the slurry to travel a longer distance before completely melting. In addition, the progressively steeper absolute slope of each curve with increasing flowing distance reflects a continuous enhancement in the melting rate of the ice slurry during the flow process. In the early stage of the ice slurry flow, the curve associated with higher flow velocity exhibits a smaller absolute slope compared to that of lower flow velocity, indicating a slower initial melting rate. This phenomenon is also attributed to the insufficient heat exchange at each position due to the

shorter residence time of the high-velocity ice slurry during the initial stage of flow.

Fig. 14 shows the variation of wall shear stress and final pipe flow velocity with respect to the initial flow velocity of the ice slurry, under a constant injection length of 13.5 m and a concentration of 70 %. When driving the ice slurry with the same length and concentration, a higher initial flow velocity requires a higher pump power, leading to a higher final flow velocity after the ice slurry has fully melted. Furthermore, as the initial flow velocity of the ice slurry increases, a steeper velocity gradient develops near the pipe wall, resulting in a higher wall shear stress, as illustrated by the red curve in Fig. 14. The magnitude of the increase in wall shear stress tends to grow slightly with higher flow velocities.

During the ice slurry flow process, a lower flow velocity allows for a longer contact time and higher heat exchange between the ice slurry and the pipe wall, resulting in a faster melting of the ice particles. For the pipe cleaning process, the ice slurry should therefore flow at a relatively high velocity, slowing down its melting rate, and thereby reducing the amount of the ice slurry required. However, a higher flow velocity will also increase frictional resistance within the pipe, leading to a larger pressure drop, which will influence pumping efficiency. If the flow resistance of the ice slurry surpasses the pipe's pressure capacity, there is a risk of pipe damage. Therefore, considering the relationship between the flow velocity, flow resistance, and pressure drop, an optimal flow velocity should be determined.

3.3. Ice slurry flowing distance prediction before full melting

To establish the most efficient ice slurry properties for pipeline cleaning, a series of relevant parameters was obtained through experiments, and a predictive formula was generated based on model fitting. Eq.(10) provides the flow length of the ice slurry.

$$L_{fm} = a \cdot l \left[b - \left(\frac{\phi}{\phi_{con}} \right)^c \cdot \left(\frac{v_0}{v_{con}} \right)^d \right] \quad (10)$$

where L_{fm} denotes the flowing distance of the ice slurry before full melting. l , ϕ , and v_0 represent the injection length, concentration and initial flow velocity, respectively. ϕ_{con} and v_{con} here are for a volume fraction of 70 % and a flow velocity of 1 m/s, respectively, while coefficients a , b , c and d , are determined by fitting the experimental data using a best-fit method, with corresponding values 3.443, 5.0165, -9.4249, and -0.1353, respectively. This equation is applicable for a 50 mm pipeline diameter within the following ranges: ice slurry injection length $l = 7.5\text{--}20$ m, ice volume fraction $\phi = 60\text{--}82$ %, and initial flow velocity $v = 0.5\text{--}1$ m/s.

Equations fitted purely through physical methods can however fail to accurately capture the experimental observations, leading to noticeable deviations. Machine learning (ML) methods have thus been widely applied in data-fitting problems, although a substantial volume of data is usually required to ensure accuracy [39]. ML methods have been widely used in the field of hydrology for instance for modelling physical model residuals [40,41]. To combine the advantages of both above-mentioned approaches, Karpatine et al. [42] proposed a general framework of theory-guided data science (TGDS) for embedding physics knowledge into machine learning.

The Gradient Boosting Regressor (GBR) machine learning method [43] was considered here to fit the residuals between the observed values and the physics-based estimates. The GBR model can improve prediction accuracy by iteratively minimizing the loss function through an ensemble of multiple shallow regression trees. Specifically, the model consists of 100 regression trees, each with a maximum depth of 3, and uses the mean squared error as the loss function, with a default learning rate of 0.1. The random state of each model was fixed at 0 to prevent overfitting and ensure reproducibility. This ensemble method incrementally builds the model by fitting new trees to the residual errors of

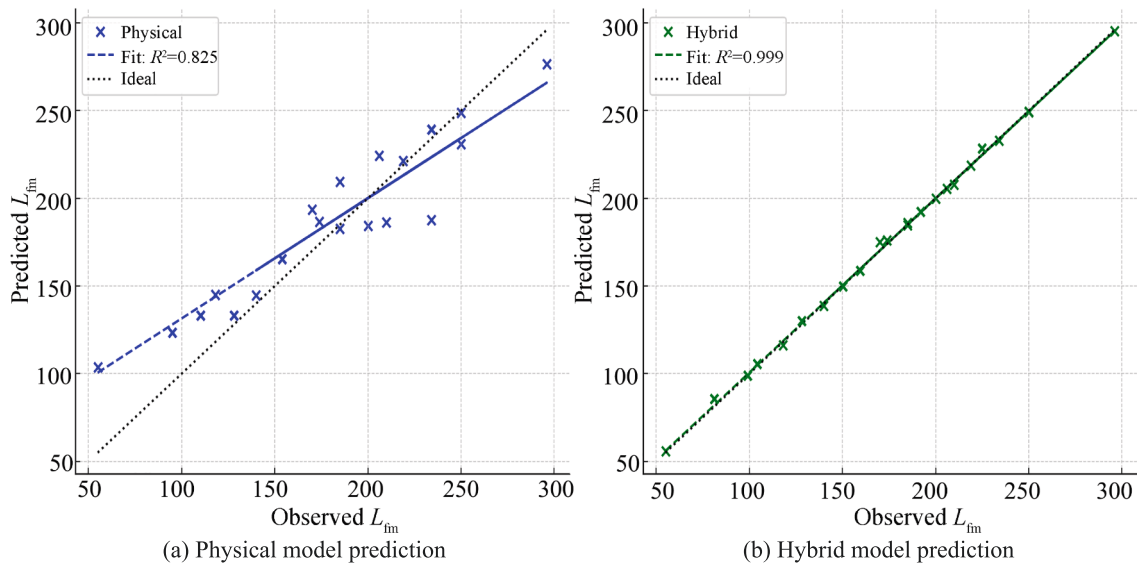


Fig. 15. Models for predicting the flowing distance of ice slurry at full melting.

the previous ensemble, effectively capturing nonlinear patterns and feature interactions. In addition, feature importance metrics were extracted to assess the relative influence of input variables on residual prediction.

A predictive formula for estimating the flowing distance of ice slurry before full melting is proposed here by combining the physical method provided through Eq.(10) with a Gradient Boosting Regressor, improving the accuracy of the physical method while requiring less data for fitting.

$$L_{fm} = a \cdot l \cdot \underbrace{\left[b - \left(\frac{\phi}{\phi_{con}} \right)^c \cdot \left(\frac{v_0}{v_{con}} \right)^d \right]}_{\text{Physical term}} + \underbrace{\Delta L_{fm,ML}(l, \phi, v_0)}_{\text{Residual term predicted by ML}} \quad (11)$$

The fitting results presented in Fig. 15 demonstrate the accuracy of the hybrid fitting method. R^2 is the coefficient of determination, representing the proportion of model interpretation variance. It ranges from 0 to 1, where higher values reflect a better fit between the model and the data. Compared to the physical method, R^2 obtained by the hybrid method improves from 0.825 to 0.999, which demonstrates the superiority of the hybrid method.

4. Conclusions

The flow and melting behavior of high-concentration ice slurry in pipelines were investigated experimentally, focusing on the temporal evolution of ice slurry flow patterns during the cleaning process, the flowing distance of ice slurry before full melting, the evolution of wall shear stress at early stage. In addition, a novel model prediction for estimating the ice slurry flowing distance was proposed. The main conclusions are as follows:

- (1) Five stages of the ice slurry cleaning process were observed, i) water flow with scattered ice particles; ii) start of ice slurry flow; iii) stable ice slurry flow; iv) end of ice slurry flow; v) sole water flow. The pipe cleaning occurs at Stage iii, i.e. when a stable ice slurry flow is present.
- (2) Melting of the ice pig mainly occurs at its front, while its rear removes and collects fouling. This is due to the large temperature difference between the slurry front and the pipe wall, and the high heat exchange at the slurry front-surrounding the water interface.

- (3) The slurry melting rate continuously increases during the flow; the flowing distance and the wall shear stress increase with injection length, concentration, and flow velocity.
- (4) A predictive model for estimating the ice slurry flowing distance has been developed by combining the physical (best-fit) method with a Gradient Boosting Regressor, offering high accuracy, low data requirements, and strong fitting performance.

Shortcomings and possible improvements have also been identified during this experimental investigation:

- (1) Since commercial pipelines are typically not closed, the flowing distances measured in experimental setups are likely to exceed those observed in actual applications.
- (2) Parameters such as ambient temperature, ice slurry concentration and the manual mixing of the ice slurry, were difficult to control precisely in the laboratory.
- (3) Data is also limited to conclude on all possible situations encountered in real systems.

Future investigations will include the development of a computational fluid dynamics (CFD) model to predict and explore additional working conditions at low cost and provide a flow map and guidance for an efficient cleaning of a pipe system through ice pigging. In addition, a more general ML-based model will be developed, with the aim to make it applicable to different pipe diameters, concentrations, velocities and thermal boundary conditions.

CRediT authorship contribution statement

Haiqin Song: Writing – original draft, Methodology, Data curation, Conceptualization. **Patrick G. Verdin:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Jinfeng Zhang:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data supporting the findings of this study are available within the article.

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Experimental investigation of flow characteristics of high-concentration ice slurry in pipes considering melting effects

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