



Research Paper

Numerical investigation of dynamic flow and melting behavior of high-concentration ice slurry for sustainable pipeline cleaning

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ARTICLE INFO

Keywords:

Ice slurry
Pipeline cleaning
Phase change
Dynamic wall temperature
Flow characteristics
Melting pattern
CFD

ABSTRACT

High-concentration ice slurry is a promising and environmentally friendly solution for energy-efficient pipeline cleaning due to its high latent heat and effective scouring ability. A novel mixture model based on the kinetic theory of granular flow incorporating a phase-change melting model and a dynamic wall temperature function has been developed to simulate the dynamic flow and melting behavior of thick ice slurry in a horizontal pipe. Numerical simulations are compared to experimental data, and results primarily focus on the ice slurry flowing distance before complete melting, effective flowing distance, melting characteristics, formation and evolution of the slurry-water interface, as well as the temperature distribution across different regions of the pipe. Results confirm that injection length, concentration, and velocity of the slurry have a significant effect on its flowing distance, and that the ice slurry melting rate gradually decreases. In addition, the ice slurry exhibits a distinct edge-to-center melting pattern, with the outer layers melting first and surrounding the central region. The ice volume fraction decreases from the center toward both ends from the axial direction, and the ice volume fraction is lowest at the bottom and gradually increases with height. The front and rear interfaces between the ice slurry and water appear finger-shaped, however behaving differently due to the viscosity difference. Numerical results are shown to match well the experimental data, providing a useful numerical tool and guidance for the design and operation of ice slurry-based pipeline cleaning systems.

1. Introduction

Within energy and thermal-fluid transport systems, pipelines constitute an essential infrastructure for the efficient transport of liquid or gaseous media over long distances, but also for the management of thermal energy along the flow path. During prolonged operation, pipeline systems tend to accumulate a wide range of impurities on their internal surfaces, which will reduce the purity of the transported media, alter local heat transfer characteristics, increase flow resistance, and shorten the service life of the pipeline [1]. Pipeline cleaning therefore plays a critical role in maintaining the efficiency and reliability of pipeline transportation systems [2]. Among various cleaning methods, ice slurry pigging combines mechanical scraping by ice particles with phase-change heat transfer, enabling an efficient removal of deposits while simultaneously enhancing heat transfer and thermal performance within the system.

Conventional methods for cleaning pipelines are generally divided into chemical and physical categories. Chemical cleaning [3,4], such as

the combined use of acid and alkali solutions, removes deposits by inducing chemical reactions, but these processes may lead to pipeline corrosion and environmental contamination after long-term application. Physical cleaning, on the other hand, relies on physical forces to detach impurities from the pipe surface. Common techniques include high-pressure water jets, pig-based cleaning, gas–water pulse flushing, and manual disassembly [5–8]. Despite their technological maturity, these methods remain constrained by narrow applicability, high water consumption, operational complexity, and low cleaning efficiency. Based on the limitations of the above-mentioned methods, a more environmentally friendly and efficient option—ice slurry pigging [9]—has been proposed.

In ice slurry cleaning applications, the friction between ice particles and the pipe wall is used to remove fouling, while the melting of ice crystals absorbs heat from adhered contaminants and then induces thermal detachment due to temperature gradients. Experimental investigations by Quarini [10] demonstrated that ice slurry with a high ice fraction can effectively adapt to complex pipeline geometries due to its rheological nature, while the presence of solid particles increases wall

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<https://doi.org/10.1016/j.applthermaleng.2025.129099>

Received 30 August 2025; Received in revised form 26 October 2025; Accepted 9 November 2025

Available online 10 November 2025

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Nomenclature		Greek symbols	
A_{coeff}	Relaxation factor	α	Volume fraction, %
c_i	Ice specific heat capacity, J/(kg·K)	ε	Turbulent dissipation rate, m^2/s^3
c_w	Water specific heat capacity, J/(kg·K)	θ_s	Granular temperature, m^2/s^2
d_s	Particle diameter, m	k	Thermal conductivity, W/(m·K)
D_{in}	Pipe diameter, m	μ	Dynamic viscosity, Pa·s
e_{ss}	Restitution coefficient	π	Mathematical constant
E	Specific total energy, J/kg	ρ	Density, kg/m^3
F	Body force, N/m^3	ϕ_i	Ice volume fraction
g	Acceleration of gravity, m/s^2	ϕ_w	Water volume fraction
$g_{0,\text{ss}}$	Radial distribution function	ϕ'	Melting rate
h	Specific enthalpy, J/kg	Δt	Time step
h_L	Latent heat, kJ/kg	σ	Relative error
J	Diffusive flux, $\text{kg}/\text{m}^2\cdot\text{s}$	τ	Shear stress, Pa
$k\text{-}\varepsilon$	Turbulence model	ν	Flow velocity, m/s
L	Flowing distance, m	Subscripts	
L_p	Pipe length, m	a	ambient
l	Ice slurry injection length, m	coeff	coefficient
n	Natural number	col	collisional
P	Pressure, Pa	dr	drift
Q	Flow rate, m^3/h	eff	Effective
S_h	Source term	fd	fluid
t	Time, s	fr	fractional
T	Temperature, K	i	ice
T_{mp}	Ice melting point, K	in	internal
T_{ini}	Initial pipe temperature, K	k	Phase index
V	Total ice volume, (m^3)	kin	kinetic
CFD	Computational Fluid Dynamics	m	mixture
IVF	Ice volume fraction	mp	melting point
KTGF	Kinetic theory of granular flow	pre	previous
UDF	User-Defined Function	t	turbulent
VOF	Volume of Fluid	w	water

friction compared with water. These combined effects enable the slurry to achieve rapid and efficient cleaning with low water consumption and without secondary pollution. However, as a non-Newtonian two-phase medium involving phase change, the flow and melting of concentrated ice slurry are highly complex, warranting further detailed analysis for practical applications.

At present, most of the existing literature has focused on the rheology and thermal characteristics of low-concentration ice slurry [11–18], while studies on the dynamic flow and melting behavior of high-concentration ice slurry for pipeline cleaning are relatively limited. The main experimental investigations on high-concentration ice slurry for pipeline cleaning can be found in the literature [10,19–24]. These experimental studies focus on the cleaning of different types of fouling, flow patterns, flowing distance, pressure drop, morphology of the ice-water interface, and real-time, non-invasive methods for monitoring the ice fraction within the pipeline. Although experimental studies have provided valuable insights into the cleaning performance, flow characteristics, and thermal behavior of thick ice slurry in pipelines, such investigations are often constrained by factors such as the limited scale of test facilities, challenges in controlling ambient temperature, the accuracy of ice fraction measurements prior to injection, high equipment and operational costs, and difficulties in capturing detailed internal flow characteristics. As a result, numerical simulations have been increasingly adopted to explore the intricate internal flow mechanisms of high-concentration ice slurry within pipelines under a wide range of conditions.

The Volume of Fluid (VOF) multiphase model is primarily used to track the distinct interfaces between immiscible fluids, making it suitable for simulating gas–liquid or liquid–liquid two-phase flows with a

clear free surface [25,26]. The Euler–Lagrange model typically assumes a low volume fraction of the dispersed phase [27,28], hence this model is not suited for high-concentration ice slurry flow in pipes. Wang et al. [11] investigated the heterogeneous flow of ice slurry using the mixture model, but did not consider heat transfer or phase change in the computational domain, which neglected the influence of ice slurry melting on the flow behavior and ice particles distribution. Zhang and Shi [29] employed a 3D Euler–Euler model based on the granular flow theory to simulate ice slurry flow and melting in horizontal pipes. The results showed that, under constant wall heat flux, the local heat transfer coefficient drops rapidly in the entrance region, then stabilizes, and continues to decrease until the ice volume fraction near the wall reaches zero. Cai et al. [13,30] adopted the Euler–Euler model to explore the flow and heat transfer characteristics of ice slurry, incorporating ice melting under a constant wall heat flux. Rezaei and Pakravan [31] used the Eulerian two-fluid model to investigate the flow and melting of the ice slurry in successive U-bends, incorporating mass transfer between phases and the kinetic theory of granular flow. However, their simulations were limited to a low ice volume fraction of 10 %, and a constant wall heat flux was assumed. Hu and Tao [32] simulated isothermal ice pigging flow using an Eulerian–Eulerian model based on the kinetic theory of granular flow. However, the ice volume fraction used in the simulation was only 40 %, which is relatively low for practical ice cleaning applications, and neither ice melting nor heat transfer was considered in the model. Subsequently, Hu et al. [33] extended their work by incorporating a phase-change thermal model to further simulate the flow and melting process of ice pigging, yielding results that more closely reflect practical conditions. However, the model still lacked a dynamic wall temperature boundary condition, which may

limit its accuracy under varying thermal environments.

All the above-mentioned simulation models lacked consideration of dynamic wall temperature variations in their boundary condition settings. During ice slurry flow for pipeline cleaning, the front portion of the ice slurry melts rapidly due to the large temperature gradient, whereas the melting rate of rear portion decreases as the pipe wall has already been cooled by the preceding slurry. Consequently, applying a constant wall heat flux as a boundary condition may lead to inaccuracies of the simulation results.

In the study proposed here, contributions have been made to investigate the dynamic flow and melting behavior of high-concentration ice slurry within pipelines, including: (1) a mixture model based on kinetic theory of granular flow, extending the applicability of computational fluid dynamics (CFD) to high-concentration ice slurry scenarios; (2) a phase change model to simulate the ice slurry melting behavior during the entire flow process, improving prediction reliability; and (3) a dynamic wall temperature function to replace the constant wall heat flux boundary condition seen in previous published studies, reflecting more realistic thermal conditions. To the best of the authors' knowledge, no identical CFD-based model is currently present in the literature. In the following sections, numerical simulations primarily focus on the flowing distance of the ice slurry before complete melting, its effective flowing distance as a cleaning medium, melting characteristics during flow, the formation mechanism and evolution of the interface between ice slurry and water, as well as the temperature variations across different regions of the pipe. Key parameters extracted from the simulation work can support the design and operation of ice slurry-based pipeline cleaning systems.

2. Methodology

2.1. Mixture model

The mixture model in ANSYS Fluent was employed to investigate the transport behavior and phase-change dynamics of high-concentration ice slurry in pipeline cleaning applications. This model treats the multiphase system as a single continuum, solving the combined continuity, momentum, and energy equations, while simultaneously tracking the volume fraction of the secondary phase and the relative velocities between phases. Compared to the Eulerian-Eulerian multiphase framework, this approach often requires fewer variables and remains reliable, particularly when the particle size distribution is wide or interphase interaction laws are uncertain [34]. Additionally, it allows for the selection of granular phases and the computation of their physical properties, making it particularly suitable for simulating solid-liquid flows such as dense ice slurry in pipelines.

2.1.1. Continuity equation

The continuity equation describes the conservation of mass within a flow system. In the mixture model, the continuity equation for the mixture is as follows:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0 \quad (1)$$

where $\vec{v}_m$ denotes the mass-averaged velocity, as defined in Eq. (2), and ρ_m represents the mixture density, as defined in Eq. (3).

$$\vec{v}_m = \frac{\sum_{k=1}^n \alpha_k \rho_k \vec{v}_k}{\rho_m} \quad (2)$$

with α_k , ρ_k , and $\vec{v}_k$ the volume fraction, density, and velocity of phase k , respectively, and n the number of phases.

$$\rho_m = \sum_{k=1}^n \alpha_k \rho_k \quad (3)$$

2.1.2. Momentum equation

The momentum equation, derived from Newton's second law, describes the change in momentum of a fluid element under the influence of external forces, and serves as a core component of the Navier-Stokes equations. In the mixture model, the momentum equation for the mixture is derived by summing the individual momentum equations for all phases:

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = & -\nabla p + \nabla \cdot \mu_m \left[(\nabla \vec{v}_m + \nabla \vec{v}_m^T) - \frac{2}{3} \nabla \cdot \vec{v}_m I \right] \\ & + \rho_m \vec{g} + \vec{F} - \nabla \cdot \left(\sum_{k=1}^n \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \end{aligned} \quad (4)$$

where p is the pressure; μ_m is the viscosity of the mixture, as defined in Eq. (5); I is the unit vector; $\vec{g}$ is the acceleration of gravity; $\vec{F}$ is a body force; and $\vec{v}_{dr,k}$ is the drift velocity for the secondary phase k , as defined in Eq. (6).

$$\mu_m = \sum_{k=1}^n \alpha_k \mu_k \quad (5)$$

where α_k and μ_k are the volume fraction and viscosity of phase k , respectively; n is the number of phases.

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \quad (6)$$

where $\vec{v}_k$ is the velocity of the secondary phase k and $\vec{v}_m$ is the velocity of the mixture.

2.1.3. Energy equation

The energy equation governs the conservation of energy within a fluid flow system, accounting for the change in internal, kinetic, and potential energy of a fluid element, as well as the energy exchanged through work and heat transfer. In the mixture model, the energy equation for the mixture is as follows:

$$\begin{aligned} \frac{\partial}{\partial t} \sum_k (\alpha_k \rho_k E_k) + \nabla \cdot \sum_k (\alpha_k \vec{v}_k (\rho_k E_k + p)) \\ = \nabla \cdot \left(k_{\text{eff}} \nabla T - \sum_k \sum_j h_{j,k} \vec{J}_{j,k} + (\vec{\tau}_{\text{eff}} \cdot \vec{v}) \right) + S_h \end{aligned} \quad (7)$$

where k_{eff} is the effective conductivity, as defined in Eq. (8); E_k is the specific total energy of phase k ; T is the temperature; $h_{j,k}$ is the specific enthalpy of species j in phase k ; $\vec{J}_{j,k}$ is the diffusive flux of species j in phase k ; $\vec{\tau}_{\text{eff}}$ is effective shear stress tensor; and S_h is the source term.

$$k_{\text{eff}} = \sum \alpha_k (k_k + k_t) \quad (8)$$

with α_k the volume fraction of phase k , k_k the thermal conductivity of phase k , and k_t the turbulent thermal conductivity.

2.1.4. Granular viscosity

In the mixture model, the granular viscosity μ_s describes the effective viscosity of the mixture, arising from particle-particle interactions due to translation and collision in a dispersed solid phase. The expression of the granular viscosity typically contains three parts: the collisional, kinetic, and the optional frictional parts:

$$\mu_s = \mu_{s,\text{col}} + \mu_{s,\text{kin}} + \mu_{s,\text{fr}} \quad (9)$$

where $\mu_{s,\text{col}}$ denotes the collisional viscosity of the particle, as defined in Eq. (10) [35,36]; $\mu_{s,\text{kin}}$ is the kinetic viscosity of the particle, as defined in Eq. (11) from Syamlal et al. [36] or Eq. (12) from Gidaspow et al. [35]; and $\mu_{s,\text{fr}}$ denotes the frictional viscosity of the particle.

$$\mu_{s,col} = \frac{4}{5} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\Theta_s}{\pi} \right)^{1/2} \quad (10)$$

where α_s is the solid volume fraction; ρ_s is the solid density; d_s is the particle diameter; $g_{0,ss}$ is the radial distribution function; e_{ss} is the restitution coefficient; and Θ_s is the granular temperature.

$$\mu_{s,kin} = \frac{d_s \rho_s \sqrt{\Theta_s \pi}}{6(3 - e_{ss})} \left[1 + \frac{2}{5} (1 + e_{ss})(3e_{ss} - 1) \alpha_s g_{0,ss} \right] \quad (11)$$

$$\mu_{s,kin} = \frac{10 \rho_s d_s \sqrt{\Theta_s \pi}}{96 \alpha_s (1 + e_{ss}) g_{0,ss}} \left[1 + \frac{4}{5} g_{0,ss} \alpha_s (1 + e_{ss}) \right]^2 \quad (12)$$

2.2. Numerical simulation

2.2.1. Geometrical model and meshing

Fig. 1 presents the two-dimensional schematic of a three-dimensional circular pipe considered in this study. The pipe has a length of 250 m and an inner diameter of 50 mm. The fluid in the three-dimensional circular pipe consists of water and ice slurry. Prior to the simulation, the pipe is fully filled with water, and at the beginning of the calculation, a specific volume of ice slurry is injected into the pipe from the pipe inlet, followed by the continuous injection of water to drive the ice slurry forward.

The mesh of the three-dimensional circular pipe computational domain shown in Fig. 2 was generated with ANSYS ICEM CFD. An O-grid blocking strategy was considered to generate the structured mesh, since this mesh type provides faster solution convergence with a lower number of cells compared to an unstructured mesh. The overall quality of the grid was above 0.8, and the minimum angle was greater than 20°, showing that a good quality mesh was obtained. A mesh independence study was carried out, which is described in detail in Section 2.2.3.

2.2.2. Model selection and boundary conditions

Transient numerical simulations of the flow field in a three-dimensional circular pipe were carried out using ANSYS FLUENT using a time-step size of 0.01 s with 20 iterations per time step. The time step was chosen based on the Courant-Friedrichs-Lewy (CFL) condition and convergence stability. A CFL number of 4 was adopted under the implicit transient scheme for the pipe model with a total length of 250 m. Although being high even for an implicit formulation, this value was verified to produce consistent results without affecting the predicted pressure drop and ice fraction evolution while maintaining reasonable computational efficiency.

The mixture model combined with the kinetic theory of granular flow (KTGF) was selected as the multiphase flow model, and the standard $k-\epsilon$ turbulence model was employed to capture turbulence effects within the three-dimensional (250 m long and 50 mm inner diameter) circular flow domain. The pressure-velocity coupling was resolved using the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm, the PRESTO! (PREssure STaggering Option) scheme was applied for pressure interpolation, and a 1.0×10^{-4} convergence criterion was applied for all equations.

Inlet and outlet boundary conditions were defined as ‘velocity inlet’ and ‘pressure outlet’, respectively. The inlet fluid properties, including fluid type, temperature, and volume fraction of the solid phase were

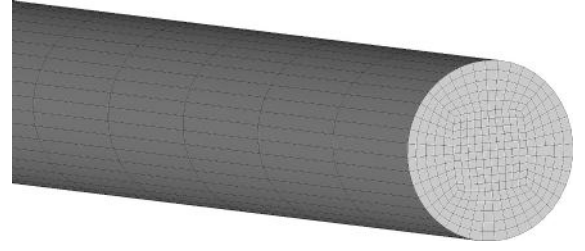


Fig. 2. Structured mesh of the 3D computational domain.

dynamically defined through a User-Defined Function (UDF). Similarly, the wall temperature was dynamically specified through the UDF, see algorithm presented in Fig. 3. T_{fluid} , $T_{\text{wall,pre}}$, and $T_{\text{wall,new}}$ represent the fluid temperature, previous wall temperature, and new wall temperature, respectively. A_{coeff} describes a dimensionless relaxation factor, governing the rate at which the wall temperature approaches the fluid temperature. As shown in Eq. (13), its actual value depends on the convective heat transfer coefficient (h), time step (Δt), wall thickness (δ_s), wall density (ρ_s) and wall specific heat capacity (c_s) [37].

$$A_{\text{coeff}} = \frac{h \Delta t}{\rho_s c_s \delta_s} \quad (13)$$

However, since the pipe wall thickness was not considered in the

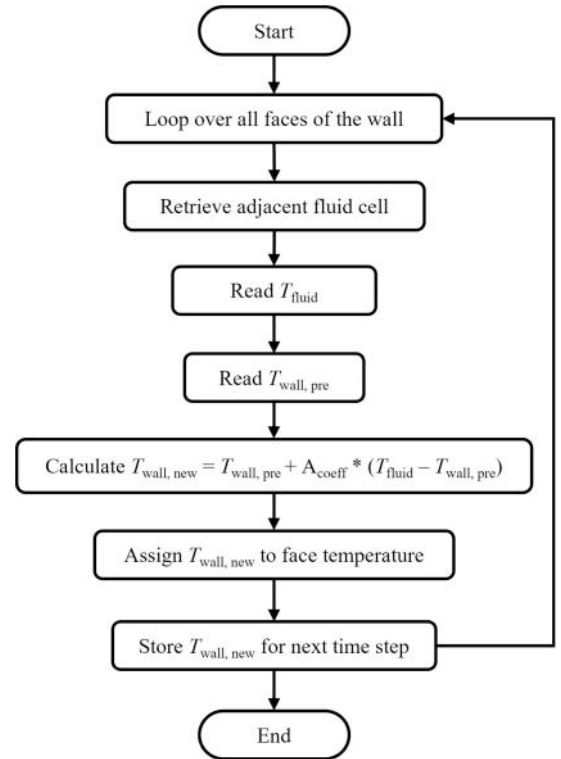


Fig. 3. Algorithm for wall temperature update within the UDF.

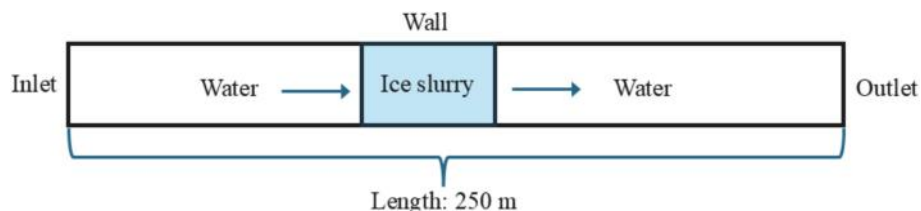


Fig. 1. Schematic of three-dimensional circular pipe.

present numerical simulation, an empirical discrete value was used instead. Trial and error calculations showed that when $A = 0.1$, the simulated results deviated from the experimental data by less than 20 %, which is deemed within acceptable accuracy range.

The phase change of the ice slurry in the pipe system was also modelled using a UDF, as illustrated in Fig. 4. The process is governed by the relationship between temperature and the melting point, along with the corresponding ice and water volume fractions. When melting or freezing occurs, the respective rate is evaluated, and the volume fraction for each phase is calculated. Finally, the phase volume fractions are constrained within the physical range [0,1] and then updated. The mathematical formulations for the ice and water volume fractions are presented in Eq. (14), while the melting rate of ice crystals is defined through Eq. (15).

$$\begin{cases} \phi_{i,n+1} = \phi_{i,n} - \phi' \Delta t, & 0 < \phi_i < 1 \\ \phi_{w,n+1} = \phi_{w,n} + \phi' \Delta t, & 0 < \phi_w < 1 \end{cases} \quad (14)$$

where $\phi_{i,n}$ and $\phi_{i,n+1}$ represent the ice volume fractions before and after one iteration update at the current time step; $\phi_{w,n}$ and $\phi_{w,n+1}$ represent the water volume fractions before and after one iteration update at the current time step; ϕ' denotes the melting or freezing rate of the ice slurry; Δt corresponds to the physical time step size; ϕ_i and ϕ_w represent the ice and water volume fraction respectively.

$$\phi' = \begin{cases} \frac{(T - T_{mp})c_i}{h_L}, & T \geq T_{mp} \text{ \& } \phi_i > 0; \\ -\frac{(T_{mp} - T)c_w}{h_L}, & T < T_{mp} \text{ \& } \phi_w > 0; \\ 0, & \text{otherwise.} \end{cases} \quad (15)$$

where T is the fluid temperature; T_{mp} is the melting point of ice particles; h_L is the latent heat of the ice slurry; c_i and c_w are the specific heat capacity of ice and water, respectively.

At the start of the simulation, the computational domain was initialized with water at 20 °C, flowing axially at a uniform velocity of 1 m/s. The initial ice volume fraction was set to zero, indicating that no ice particles were present in the domain prior to the injection of the ice slurry.

2.2.3. Mesh independence study

Since the mesh resolution may significantly affect the accuracy of the numerical results, a mesh independence study was performed. Table 1 summarises the ice volume fraction value at a point located 5 mm below the upper wall on the cross-section 5 m downstream of the inlet, obtained with five different mesh densities. As shown in Fig. 5, the value gradually decreases with the increase of cells and tends to stabilise when the number of cells reaches 14.99×10^5 . At this mesh resolution, the relative error compared to the result obtained with the finest mesh

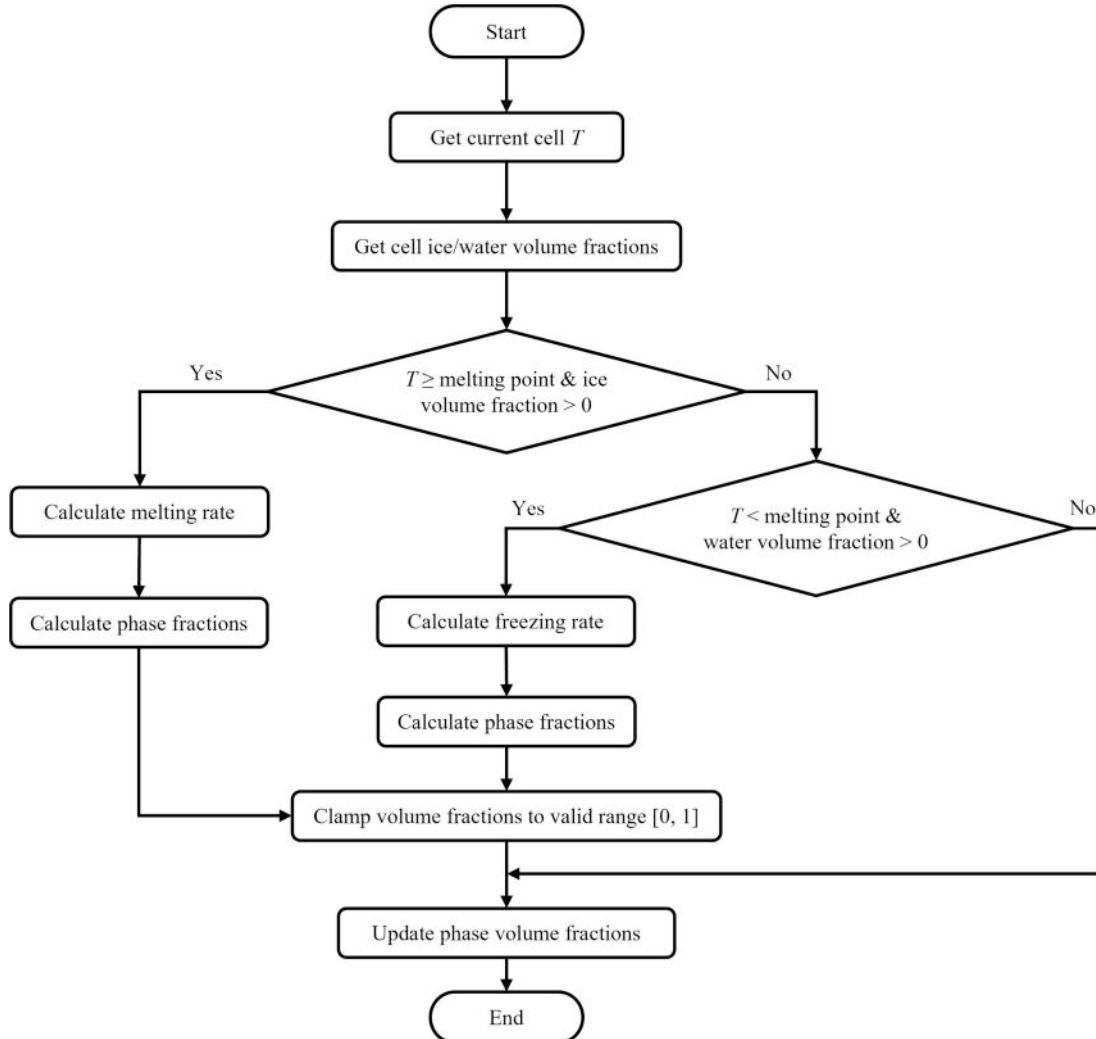


Fig. 4. Algorithm for ice slurry phase change within the UDF.

Table 1
Summary of mesh independence study.

Case	Number of cells ($\times 10^5$)	Ice volume fraction	Relative error
1	1.81	0.7060	0.57 %
2	3.65	0.7038	0.35 %
3	7.34	0.7018	0.15 %
4	14.99	0.7004	0.01 %
5	30.51	0.7003	—

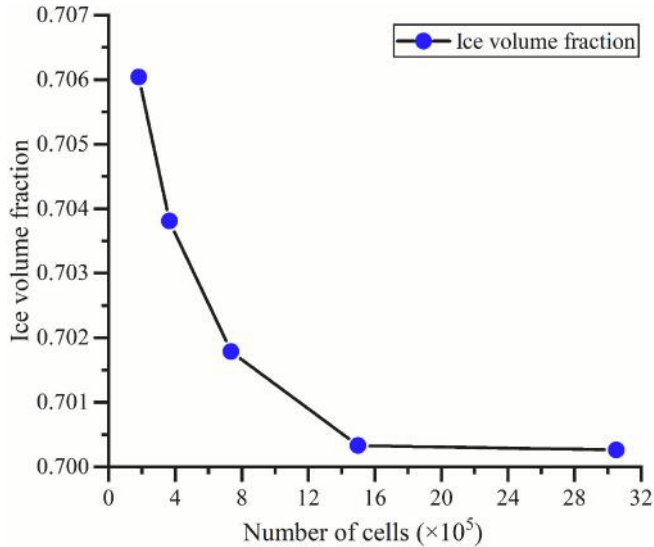


Fig. 5. Mesh independence study.

resolution (approximately 3 million cells, Case 5) is 0.01 %, as presented in Table 1. This shows that mesh independent results have been obtained. Considering both simulation accuracy and computational cost, Case 4 was selected as the optimal mesh for all subsequent simulations.

2.3. Model validation

2.3.1. Experimental settings

Fig. 6 shows the apparatus used to investigate the flowing distance and melting behavior of the high-concentration ice slurry in the pipe system. The apparatus includes two parts: the first is an ice slurry injection section, and the second is a closed-loop system through which the ice slurry circulates. The ice slurry injection section primarily consists of an injection bucket mounted above a screw pump. The closed-

loop system mainly includes several instruments, such as electromagnetic flowmeter, temperature sensor, circulating pump, frequency converter, and data acquisition system. The total perimeter of the closed-loop system is approximately 78.6 m, enabling the ice slurry to circulate until fully melted without requiring an extended straight pipe. The pipes have a nominal diameter of 50 mm, typical in engineering practice.

As shown by Numbers 5 and 6 in Fig. 6, temperature sensors were installed 2 m and 39.3 m far from the three-way valve, respectively, with the second sensor positioned at half the loop length, to monitor the temperatures of the ice slurry and water. The sampling frequency of the data acquisition card is 100 Hz. In a series of experimental tests, the ranges of key parameters—including the initial ice injection length, initial ice concentration, and flow velocity—considered are shown in Table 2. Key details of the measurement instruments are listed in Table 3.

2.3.2. Experimental uncertainty

The concentrations of the ice slurry prior to injection, the ambient temperature, the hydraulic diameter, as well as the flow rates and temperatures of both the ice slurry and water within the closed loop were recorded. To guarantee the reliability of the measurements, each parameter was measured over 20 times. For improved calculation accuracy, the highest and lowest values from each dataset were excluded. The standard uncertainty for each measured parameter was then determined using the standard deviation equation presented in Eq. (16).

$$\sigma(X) = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n(n-1)}} \quad (16)$$

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

To present the uncertainty more intuitively, the standard uncertainty was transformed into the relative uncertainty (σ_r) using Eq. (17), and the results are summarized in Table 4. It can be observed that the relative uncertainties of all measured parameters are below 1 %, indicating a

Table 2
Ranges of key parameters.

Key parameters	Range	Unit
Initial injection length, l	7.5–20	m
Initial ice volume fraction, ϕ_i	65–82	%
Flow velocity, v	0.5–1.5	m/s
Wall temperature, T_w	16–25	°C



Fig. 6. Experimental rig.

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. Symmetrical stainless-steel pipes
14. Data acquisition system
15. Water discharge bucket

Table 3
Specifications of experimental instruments.

Instrument	Type	Range	Accuracy	Notes
Screw pump	G25-1	0–5 m ³ /h	/	Inlet/Outlet: DN50/DN40; Power: 0–2.2 KW; Head: 0–60 m
Piping circulating pump	IHG50-200IB	0–21.6 m ³ /h	/	Inlet/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 ; Maximum sampling rate: 500 kS/s

Table 4
Uncertainties from measurement.

Measured parameters	Relative uncertainty, σ_r
Ice volume fraction, ϕ_i (%)	0.91 %
Ambient temperature, T_a (°C)	0.50 %
Internal diameter, D_{in} (mm)	0.83 %
Injection length of ice slurry, l (m)	0.73 %
Flow rate, Q (m ³ /h)	0.57 %
Fluid temperature, T_{fd} (°C)	0.50 %

high level of accuracy and reliability in the experimental measurements.

$$\sigma_r = \frac{\sigma(X)}{\bar{X}} \times 100\% \quad (17)$$

2.3.3. Experimental validation

The thermophysical properties adopted in the present numerical simulation are listed in Table 5. These values correspond to those of water and ice particles, representing the carrier fluid and the dispersed phase, respectively. Since ice crystals are solid particles and do not possess dynamic viscosity, the ice phase in this simulation is treated as a rigid particulate medium. The particle-phase stress is represented using the Gidaspow granular viscosity model [35], which describes the stress generated by particle collisions and friction rather than by fluid-like viscosity.

Fig. 7 presents a comparison between the experimentally obtained flowing distances of the ice slurry before complete melting, and the corresponding simulation results. The experimental conditions used to validate the numerical simulation in Fig. 7 are summarised in Table 6. To ensure consistency between the experimental setup and the numerical model, the parameter values used in the CFD settings are identical to those provided in Table 6.

The simulations considered two different wall boundary conditions: a dynamic wall temperature implemented through a UDF as detailed previously in Section 2.2.2, and a constant wall temperature. As can be seen, when considering the dynamic wall temperature condition, the

Table 5
Thermophysical parameters used in the numerical simulation.

Material	Density (kg·m ⁻³)	Specific heat (J·kg ⁻¹ ·K ⁻¹)	Thermal conductivity (W·m ⁻¹ ·K ⁻¹)	Dynamic viscosity (Pa·s)	Granular model
Ice particle	917	2100	2.2	–	Gidaspow
Water	998	4182	0.6	0.001	–

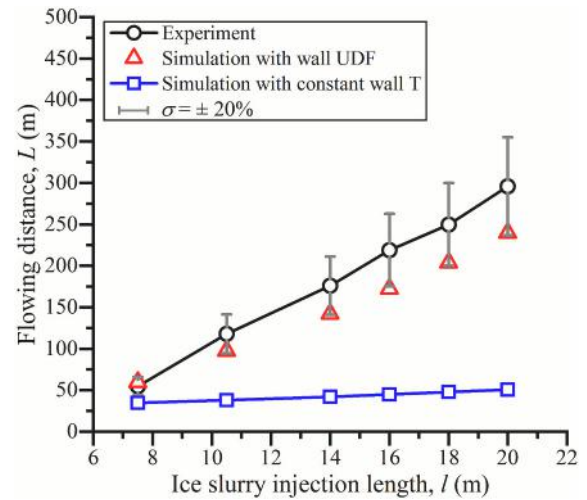


Fig. 7. Validation of the CFD simulation model with experimental data.

Table 6
Experimental conditions used to validate the numerical simulation.

Key parameters	Experimental value
Initial ice volume fraction, ϕ_i	70 %
Flow velocity, v	1 m/s
Ice slurry injection length, l	7.5–20 m
Ice particle diameter, d_s	0.01 mm
Initial pipe temperature, T_{ini}	20 °C
Pipe diameter, D_{in}	50 mm

simulated flowing distance (L) increases significantly with the ice slurry injection length (l), whereas L only increases slightly when the wall temperature is considered constant. It appears clearly that the simulation results carried out with a dynamic wall temperature are in closer agreement with the experimental data and within a $\pm 20\%$ error.

Simulated results are however generally underpredicted. For the CFD model, a long straight pipe open at its outlet is considered, which allows the fluid to propagate in a single main direction. However, in the experimental settings, the pipe system is a closed loop because of site limitations, making the flow to recirculate, see Fig. 6. The temperature within the experimental closed-loop system therefore drops after each test, resulting in the initial temperature of the pipe system being slightly different for each case, hence lower than for the CFD simulations. This would explain that the measured flowing distances are slightly higher than the predicted ones. Unfortunately, this problem could not be avoided/controlled in the laboratory. It is thus the opinion of the authors that the predicted numerical results actually align more closely with engineering conditions, which would indicate that the numerical model proposed in this study exhibits good predictive accuracy.

3. Results and discussion

3.1. Flowing distance of ice slurry before complete melting

This section describes and discusses the flowing distance of ice slurry before complete melting under varying injection lengths,

concentrations, and pipe flow velocities. A systematic comparison of the results is presented to highlight the effects of these parameters on both the melting process and the transport characteristics.

3.1.1. Effect of ice slurry injection length on flowing distance

Fig. 8 shows the decrease of the total volume of ice in the pipe over time for different ice slurry injection lengths. Although melting occurs continuously due to the temperature difference between the slurry and its surroundings, the melting rate is significantly lower than the injection rate during the ice slurry injection phase. Consequently, the total amount of ice within the pipe increases steadily initially. Once the injection is complete, the total ice volume reaches its maximum value—corresponding to the peak of the curves. The total ice volume then gradually decreases as melting occurs. Meanwhile, the ice slurry's melting rate gradually declines, as indicated by the magnitude of the curve's slope. The ice slurry has the same injection concentration (70 % volume fraction) and velocity (1 m/s) for each of the four scenarios illustrated in Fig. 8. Therefore, the time at which the total ice volume in the pipe reaches zero can be used to determine the slurry flowing distance before ice slurry is fully melted. Based on the observed trends, the ice slurry flowing distance exhibits a rather linear increase with increasing injection length.

3.1.2. Effect of ice slurry injection concentration on flowing distance

Fig. 9 presents the variation of total ice volume in the pipe over time for different initial ice volume fractions (IVF). As the injection duration (14 s) and flow velocity (1 m/s) are identical, the total ice volume in the pipe reaches its maximum simultaneously at the end of the injection phase for all three cases. Subsequently, the total ice volume decreases gradually until it reaches zero. The difference of maximum total ice volume in the pipe between all three cases is minimal, as the simulated pipe has a small diameter of only 50 mm, which limits the impact of concentration differences on melting rate and flowing distance. However, the curves in Fig. 9 still reveal that the higher-concentration ice slurry takes a slightly longer time to fully melt, which indicates a slightly longer flowing distance.

3.1.3. Effect of flow velocity on flowing distance

The total ice volume in the pipe changes over time under different flow velocities, as illustrated in Fig. 10. An identical quantity and concentration of ice slurry is injected into the pipeline for three different flow velocities. The injection duration becomes shorter with increasing flow velocity, and the peak of total ice volume becomes higher, as indicated by points A, B, and C corresponding to velocities of 0.5, 1.0

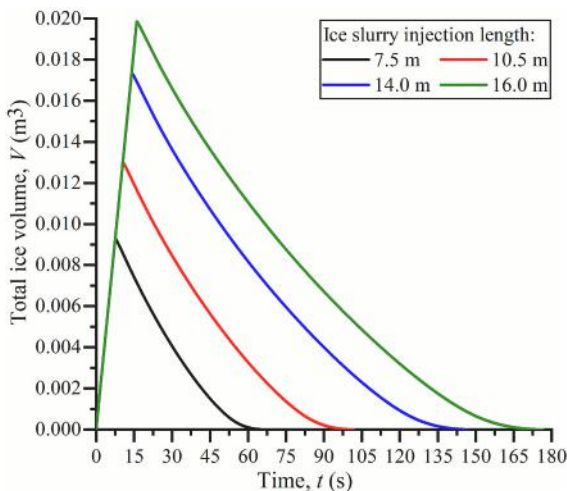


Fig. 8. Variation of total ice volume in the pipe over time under different slurry injection lengths.

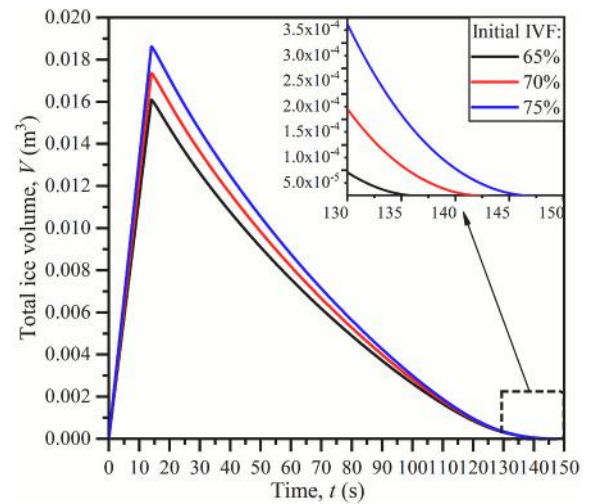


Fig. 9. Variation of total ice volume in the pipe over time under different injection concentrations.

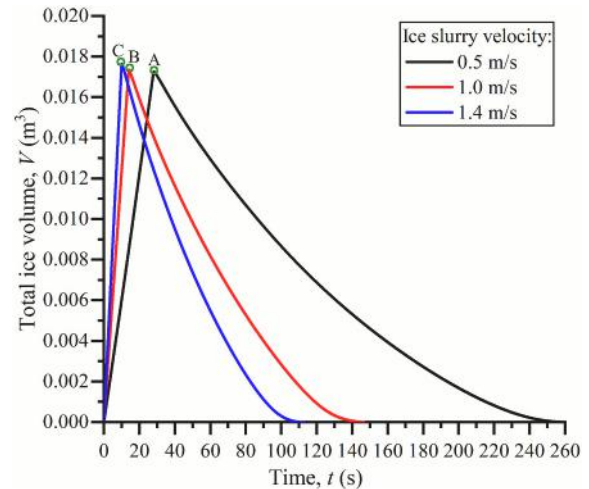


Fig. 10. Variation of total ice volume in the pipe over time under different flow velocities.

and 1.4 m/s, respectively. At higher velocities, a large volume of ice slurry is introduced into the pipe in a shorter period, allowing less time for melting during the injection phase. In contrast, under lower flow velocities, the injection takes more time, providing more time for partial melting to occur during the injection phase. During the decrease of the total ice volume, the ice slurry with higher flow velocity exhibits a faster melting rate compared to that with lower velocity. This however does not mean that the corresponding flowing distance is shorter. Based on the flow time and velocity of the ice slurry, the flowing distances of ice slurry at the point of complete melting are 125, 140, and 153 m for flow velocities of 0.5, 1.0, and 1.4 m/s, respectively.

3.2. Effective flowing distance of ice slurry

When used as a cleaning medium, ice slurry undergoes a gradual decrease in concentration along the pipeline due to its continuous melting. Once the ice slurry concentration drops below a critical value, its effectiveness as a cleaning medium is significantly diminished. To date, there has been very limited research reported in the literature regarding this critical value. Evans et al. [24] installed ultrasonic sensors across the cross-sectional direction of the pipe to monitor the concentration of the ice slurry flowing through and defined a volume fraction of

15 % as the threshold value. The ice slurry was considered no longer effective for cleaning, when its concentration fell below this value. Accordingly, this study also adopts a volume fraction of 15 % as the threshold to evaluate the effective flowing distance of the ice slurry.

Fig. 11 illustrates the variation in ice volume fraction (IVF) at different cross-sections of the pipe under four different ice slurry injection lengths, all with the same initial concentration (70 % ice volume fraction) and flow velocity (1 m/s). The interval covered by each curve along the horizontal axis represents the time during which ice slurry passes through the corresponding cross-section. As the cross-sectional position increases, the time interval gradually decreases until it reaches zero. In addition, the IVF peak value seen at each cross-section shows a decreasing trend. Taking 15 % IVF as the threshold, it can be established that with increasing cross-sectional position, the effective length of the ice slurry (IVF > 15 %) decreases at a faster rate than its total remaining length. When the maximum ice volume fraction of residual ice slurry falls below 15 %, its cleaning capability is regarded as negligible.

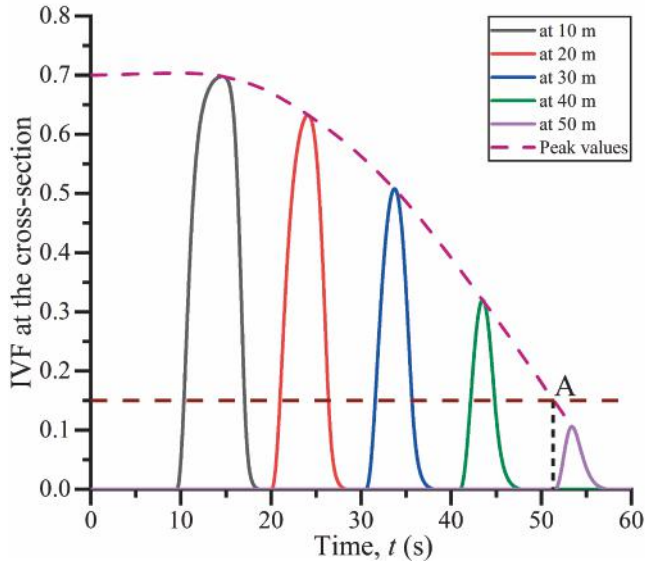
Taking Fig. 11(a) as an example, when the residual ice slurry passes

through the cross-section located at 40 m along the pipe, its maximum ice volume fraction is greater than 15 %, as indicated by the cyan curve. This suggests that the effective flowing distance of the ice slurry exceeds 40 m. Similarly, when the residual ice slurry passes through the cross-section located at 50 m, its maximum ice volume fraction falls below 15 %, as shown by the purple curve. This indicates that the effective flowing distance of the ice slurry is less than 50 m. Combining the above two analyses, it can be concluded that the final effective flowing distance of the ice slurry lies between 40 and 50 m. Therefore, based on the intersection points A, B, C, and D, the effective flowing distances of the ice slurry under all four different injection lengths are approximately 47, 75, 112, and 134 m, respectively.

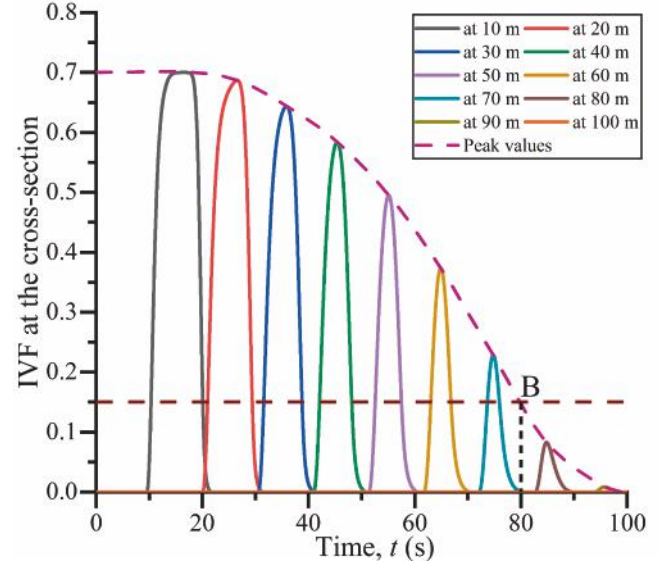
3.3. Ice volume fraction distribution during ice slurry flow

3.3.1. Axial cross-sectional distribution of ice volume fraction

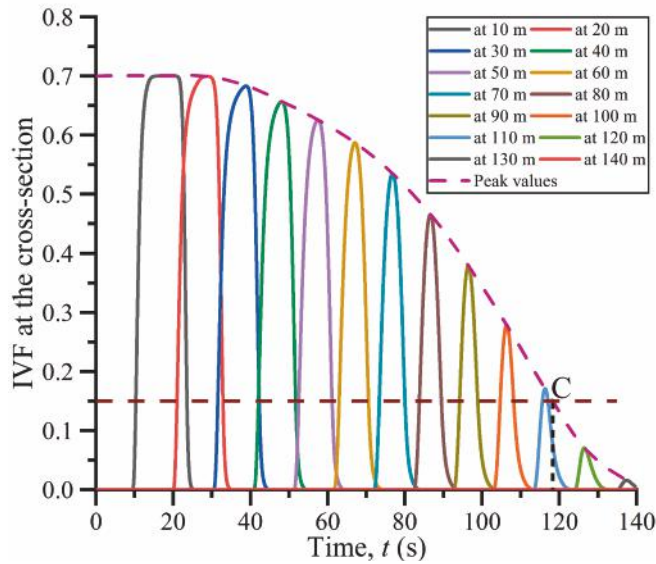
Fig. 12 shows the axial cross-sectional distribution of ice volume fraction along the pipe at different times of the simulation. Because the pipe model has a diameter of 50 mm and a total length of 250 m, the



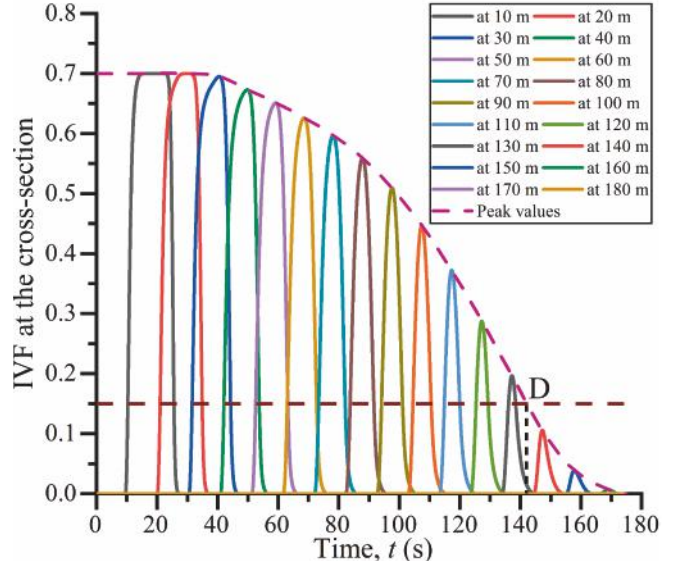
(a) 7.5 m ice slurry injection



(b) 10.5 m ice slurry injection



(c) 14 m ice slurry injection



(d) 16 m ice slurry injection

Fig. 11. Variation curves of ice volume fraction at different cross sections.

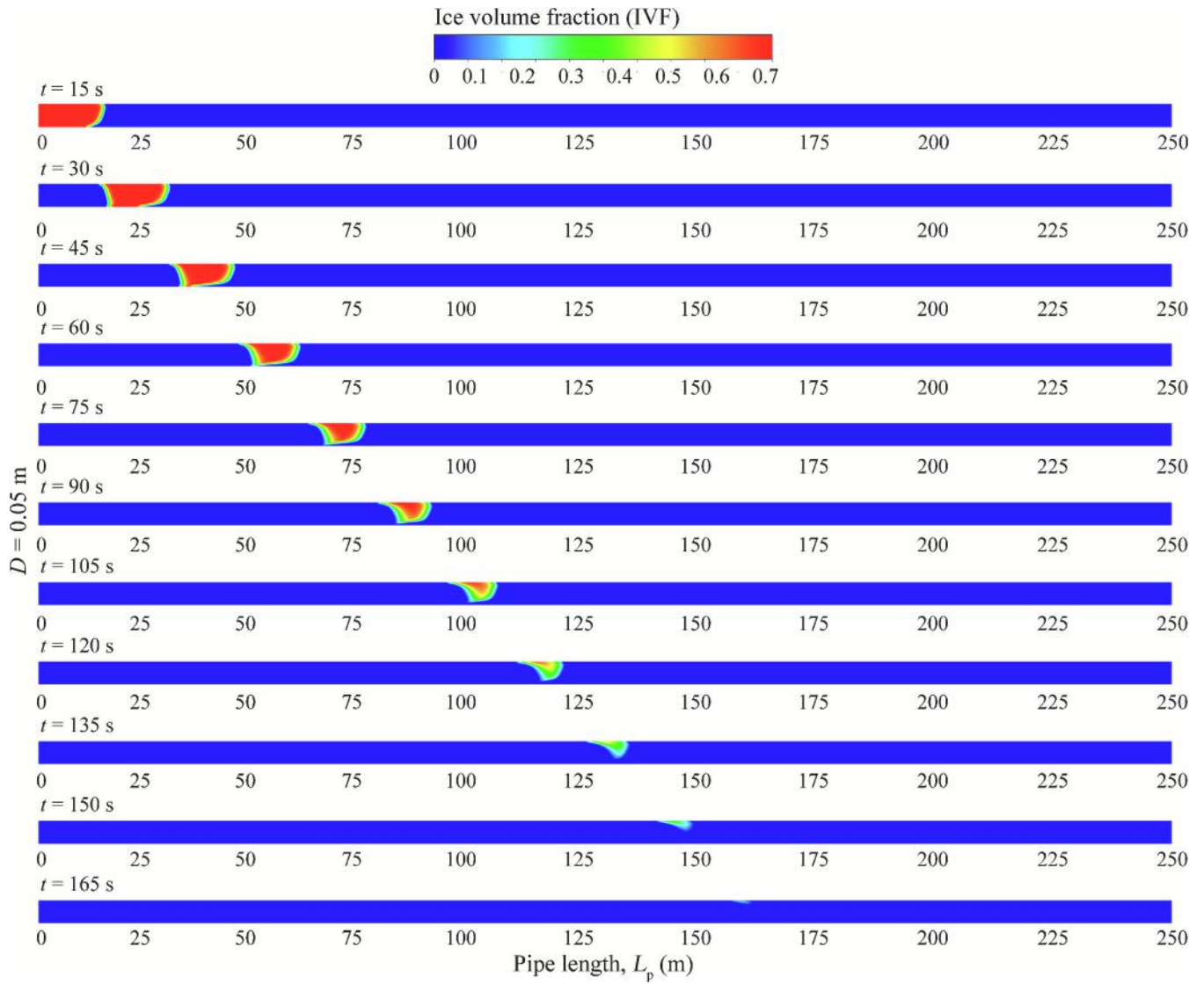


Fig. 12. Axial cross-sectional distribution of ice volume fraction.

axial dimension was scaled down by a factor of 100 for better visualization. During the flow process, the remaining length of the ice slurry within the pipe progressively decreases and eventually becomes zero.

3.3.2. Cross-sectional distribution of ice volume fraction

Fig. 13 shows the distribution of ice volume fraction with an initial length of 16 m and an initial volume fraction of 70 %, on the pipe cross-section when the ice slurry has flowed for 50 s. For better visualization, the axial dimension was scaled down by a factor of 200.

From the ice volume fractions obtained at the cross-sections (located at axial positions of 34 and 50 m), it can be established that the remaining ice slurry length has decreased to less than 16 m due to melting. The ice volume fraction observed at the 42 m cross-section is significantly high. From the axial perspective, the ice volume fraction decreases from the center toward both ends. In the cross-sectional view, it exhibits a symmetric distribution. Vertically, a clear concentration gradient is observed: the ice volume fraction is lowest at the bottom and gradually increases with height. During the flow of the ice slurry, the top

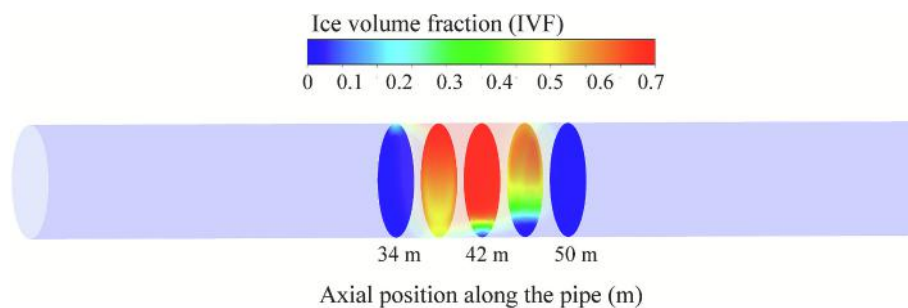


Fig. 13. Cross-sectional distribution of ice volume fraction at $t = 50$ s.

layer is continuously in contact with the upper pipe wall and thus melts first due to the temperature difference. In addition, because the density of ice is lower than that of water, ice particles from the lower region tend to migrate upward, resulting in the highest ice volume fraction being consistently maintained near the top.

3.4. Interface characterization between ice slurry and water

Fig. 14 shows the interface characterization between ice slurry and water at different times. In the figure, the axial dimension was compressed by a factor of 10 for clarity. The rear interface is formed by the water at the back driving the ice slurry forward. When low-viscosity water drives the high-viscosity ice slurry, the large viscosity difference induces interfacial instability, resulting in finger-like intrusions of water into the ice slurry.

As time progresses, the rear interface gradually narrows and exhibits increasing instability. The front interface is formed by the slurry pushing the water in front of it. In contrast to the rear interface, the front interface appears finger-shaped, but the ice slurry does not intrude into the water and the ice slurry at the front interface consistently resides above the boundary. Over time, the front interface gradually becomes narrower and more pointed, with a distinct concentration gradient observed around the interface region. Since the ice slurry with a higher viscosity pushes the lower-viscosity water, the front interface remains stable, continuous, and smooth. At $t = 150$ s, the ice slurry has melted to the point where only a thin layer remains near the top of the pipe and the front and rear interfaces between the ice slurry and water have merged into a single interface.

3.5. Temperature variation of the fluids in the pipe

Fig. 15 presents the temperature variation of the fluids in the pipe. The axial dimension was scaled down by a factor of 100 for better visualization purposes. The scale at the top ranges from 273.15 to 293.15 K (0 to 20 °C). At $t = 15$ s, the pipe is still in the ice slurry injection stage, and its temperature distribution is divided into three regions from left to right: ice slurry, front interface, and original water. At this time, the temperature is 0 °C in the blue region, which, as shown previously in Fig. 12, corresponds to ice slurry composition. At $t = 30$ s, the temperature distribution in the pipe consists of five distinct regions: driving water, rear interface, ice slurry, front interface, and original

water. At this time, the blue region begins to shrink, and the color at both ends becomes lighter. This is because the ice slurry at both ends has melted into water at about 1 °C, which also indicates that the fluid in the initial blue region is no longer entirely constituted of ice slurry. With the flow and melting of the slurry, the temperature gradient around the interface increases, and the low-temperature region (0–2 °C) becomes increasingly smaller. It should be noted that since the 0 °C ice slurry absorbs heat and melts into 0–1 °C water, it becomes difficult to distinguish whether the low-temperature region (blue zone) still contains ice slurry. Therefore, those results should be interpreted in conjunction with those reported in Fig. 12.

To further quantify the relationship between the temperature field and the ice volume fraction distributions, the residual lengths of the low-temperature region (from Fig. 15) and the ice slurry (from Fig. 12) were extracted and plotted as functions of time, see Fig. 16. Both curves exhibit a decreasing trend with time, confirming the progressive melting of the ice slurry and the corresponding shrinkage of the low-temperature zone. However, the decrease rate of the low-temperature region (blue squares) is considerably slower than that of the ice slurry (orange circles). Specifically, the ice slurry length decreases almost linearly from about 15.2 m at $t = 30$ s to nearly 0 m at $t = 165$ s, while the low-temperature region length reduces only slightly from about 15.6 m to 10.5 m during the same period. This difference originates from the thermal inertia and phase transition characteristics of ice slurry. When the solid ice particles melt, the resulting meltwater remains at approximately 0–2 °C, forming a cold-water region that still appears as “blue” in the temperature contours, although it no longer contains solid ice. The above analysis therefore explains the physical mechanism responsible for the discrepancy between the shrinkage rates of the low-temperature zone and the residual ice slurry length, providing a clear quantitative link between the temperature and phase distributions. It should be noted that as the fluids progress along the pipe, the low-temperature region gradually disappears, and a nearly uniform temperature distribution is eventually established due to continuous heat exchange along the pipe.

3.6. Distribution of wall static temperature

Fig. 17 presents the distribution of static temperatures along the pipe wall. The axial dimension was scaled down by a factor of 100 for better visualization purposes. The scale at the top ranges from 273.15 to 293.15 K (0 to 20 °C). Compared with Fig. 15, it can be seen that the wall

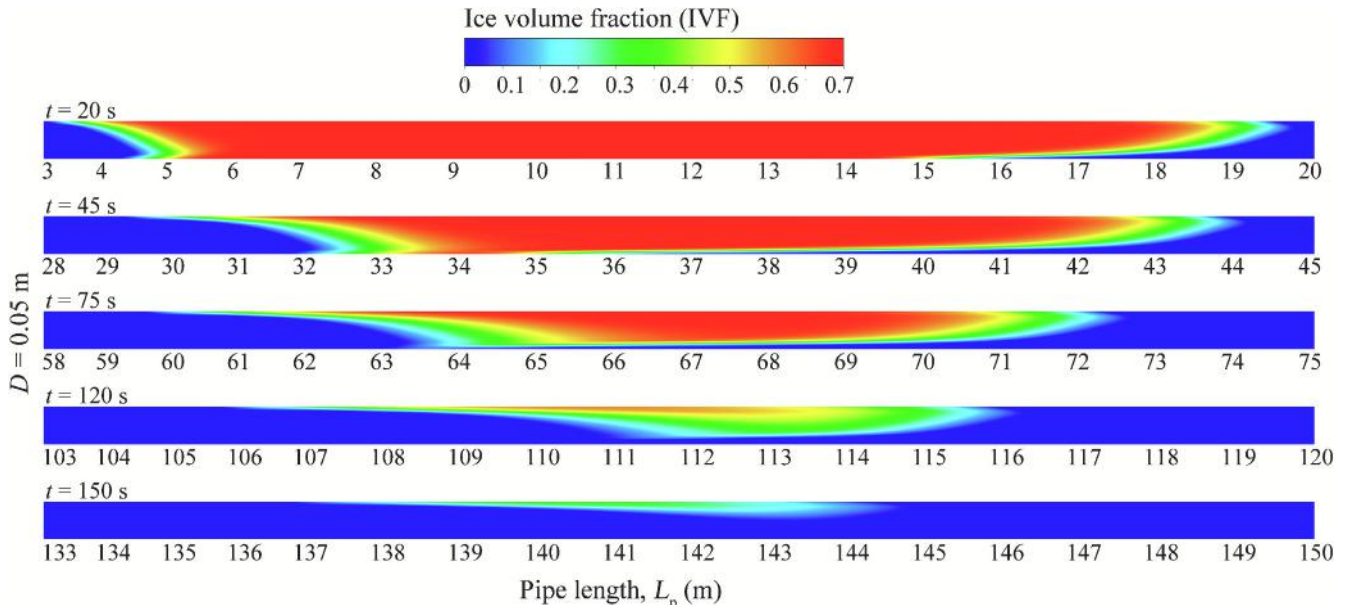


Fig. 14. Interface characterization between ice slurry and water.

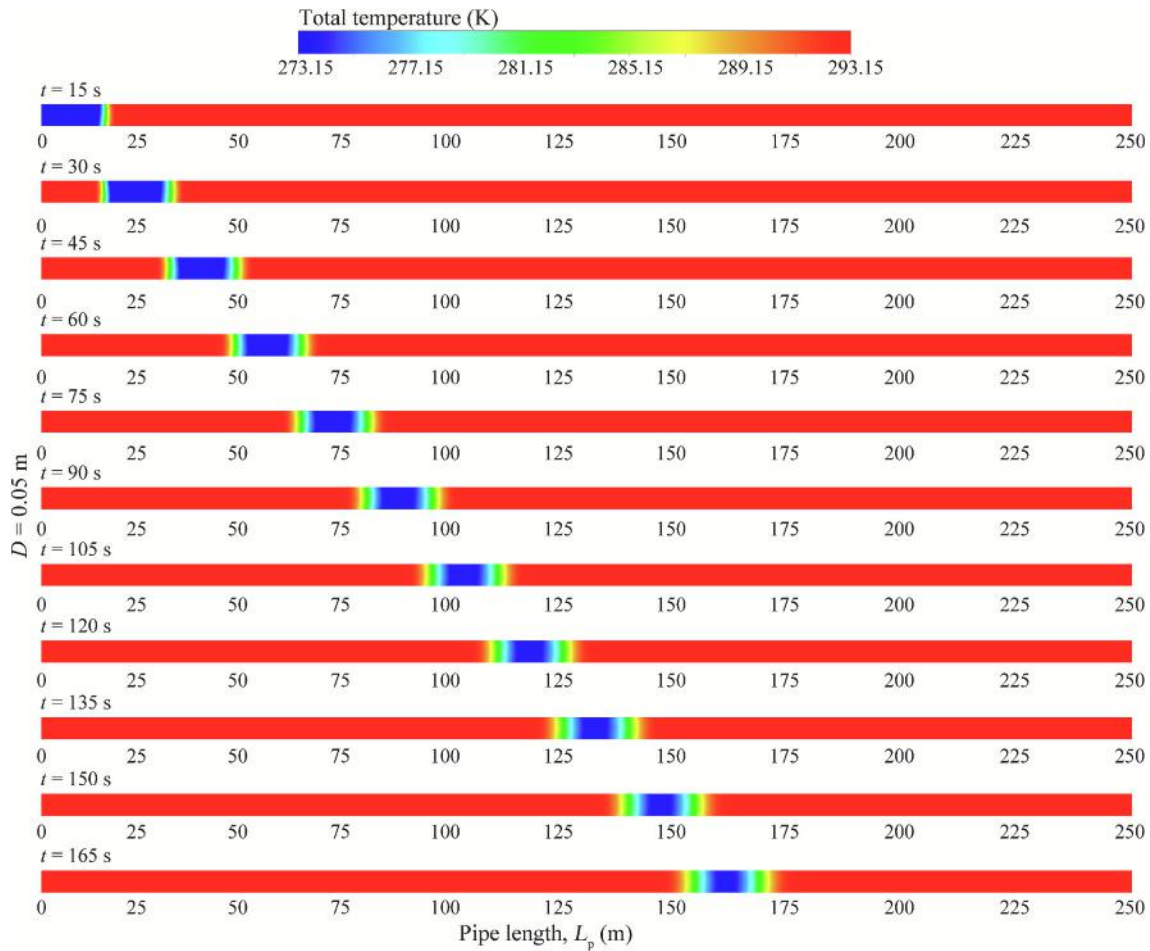


Fig. 15. Temperature variation of fluids in the pipe.

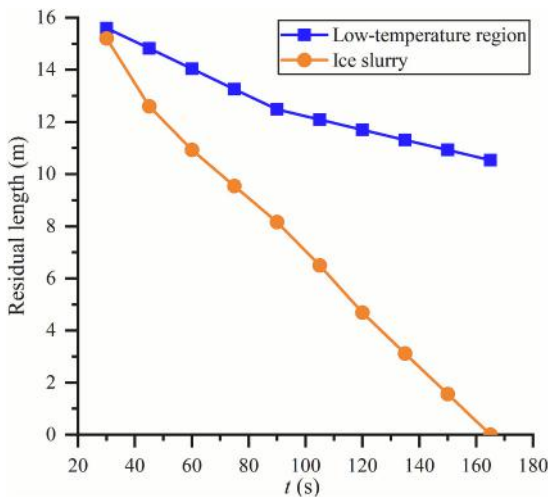


Fig. 16. Time-dependent variation of the residual length of low-temperature region and ice slurry in the pipe.

temperature distribution exhibits a similar trend to the temperature variation of the fluids inside the pipe. At $t = 15$ s, the pipe is still in the ice slurry injection stage; therefore, the wall temperature near the pipe inlet remains at 0°C . A distinct temperature gradient appears on the wall surface corresponding to the mixing region between the injected ice slurry and the original water in the pipe. The remaining wall surfaces maintain the temperature corresponding to the original water in the

pipe (20°C). As the ice slurry continues to move forward, the wall temperature behind the ice slurry gradually rises to 20°C due to the presence of the propelling water, while the wall temperature ahead of the ice slurry still remains at about 20°C . Meanwhile, the temperature gradient at the ice slurry-wall interface continues to increase. As the fluids progress along the pipe, this gradient gradually diminishes, and a uniform wall temperature distribution is eventually established because of a continuous heat exchange along the pipe.

4. Conclusions

A mixture model based on the kinetic theory of granular flow, incorporating a phase-change melting model and a dynamic wall temperature function, was developed to simulate the dynamic flow and melting behavior of thick ice slurry in a horizontal pipe. A series of numerical simulations were conducted to 1) quantify the ice slurry flowing distance before complete melting, and the effective flowing distance of ice slurry as a cleaning material under various injection conditions, 2) analyze the melting patterns during ice slurry flow, 3) explore the evolution of the interface between the ice slurry and water, and 4) study the temperature variations of the ice slurry and the surrounding interface during the flow process. The main conclusions are as follows:

- 1) Although expected, the study has demonstrated that the injection length, concentration, and velocity of the ice slurry have a significant effect on its flowing distance. The flowing distance of the ice slurry before complete melting increases as these parameters increase. The melting rate of the ice slurry during the flow process gradually

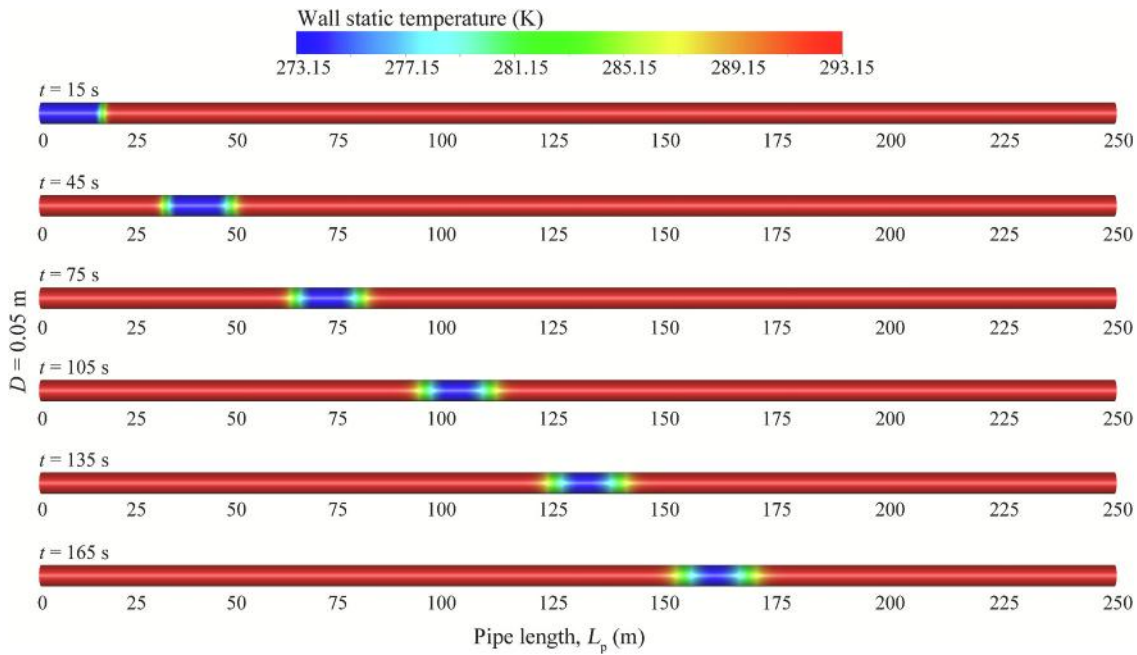


Fig. 17. Distribution of wall static temperature.

decreases and eventually approaches zero. In addition, the effective flowing distance of ice slurry—defined by a critical volume fraction threshold of 15 %—was determined based on IVF variations along the pipe. Under injection lengths of 7.5, 10.5, 14, and 16 m, the corresponding effective flowing distances were approximately 47, 75, 112, and 134 m, respectively.

- 2) During the flow process, the ice slurry exhibits a distinct edge-to-center melting pattern, with the outer layers melting first and surrounding the central region. From the axial perspective, the ice volume fraction decreases from the center toward both ends. In the cross-sectional view, it exhibits a symmetric distribution. Vertically, a clear concentration gradient is obtained: the ice volume fraction is lowest at the bottom of the ice slurry layer, and it gradually increases with height.
- 3) The front and rear ice slurry-water interfaces appear finger-shaped, but they behave differently due to the viscosity difference between them, eventually merging into a single interface as melting progresses.
- 4) With the flow and melting of the ice slurry, the temperature gradient around the interface increases, and the low-temperature region gradually shrinks. As the fluids progress through the pipe, a uniform temperature distribution is eventually achieved due to the heat exchange.

This study provides some guidance and references for the design and operation of ice slurry-based pipeline cleaning. Future research will focus on long-distance flows and phase change behavior in complex pipeline configurations, including right-angle bends, S- and U-shaped geometries. A previously developed model for solidification problems including both slurry and mushy regions treatment [38] could also be modified and adapted to further study high-concentration ice slurry in pipelines.

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.

Acknowledgement

No funding has been received for this research.

Data availability

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

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Numerical investigation of dynamic flow and melting behavior of high-concentration ice slurry for sustainable pipeline cleaning

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2026-01-30

Elsevier

<https://doi.org/10.1016/j.applthermaleng.2025.129099>

Song H, Verdin PG, Zhang J. (2026) Numerical investigation of dynamic flow and melting behavior of high-concentration ice slurry for sustainable pipeline cleaning. Applied Thermal Engineering, Volume 284, January 2026, Article number 129099