

Article

Investigation of Oil–Water Two-Phase Flow Characteristics During Water-Driven Oil Evacuation in Inclined Inverted U-Shaped Mobile Pipelines

Gang Fang, Jimiao Duan *, Yan Chen , Yongxiang Huang, Jiang Li and Jian Wang 

Joint Logistics Support Force Engineering University, Chongqing 401331, China; 18986966529@163.com (G.F.)

* Correspondence: duanjimiao@126.com (J.D.); yansohucom@sohu.com (Y.C.)

Abstract

Mobile pipeline refers to a type of pipeline that can be laid and recovered at any time as required, mainly used for product oil transportation. After the completion of the transportation mission, the oil remaining inside the pipeline needs to be evacuated before recovering. Water-driven oil evacuation is commonly used for this purpose. In this paper, the water-driven oil evacuation in an inclined inverted U-shaped pipe was investigated. A numerical model coupling the VOF interface-capturing method, the CSF surface-tension model, and the SST $k-\omega$ turbulence model was established and validated against visualization experiments. The oil–water two-phase displacement characteristics in this special pipe configuration were systematically analyzed. The results show that a critical inlet superficial water velocity exists during the evacuation process. Complete oil evacuation can be achieved only when the inlet superficial water velocity exceeds this critical value. The critical velocity increases with increasing pipe inclination angle and pipe diameter. When the inlet superficial water velocity is lower than the critical value, vortical structures and backflow are readily generated at the oil front and within the oil phase, leading to oil accumulation near the end of the upper horizontal section and the formation of a stable retained oil layer in the downward-inclined section. Moreover, larger inclination angles and pipe diameters intensify oil retention and reduce the evacuation efficiency under subcritical conditions. All conclusions are drawn based on the No. 0 diesel–water system at 25 °C, and the applicable scope is limited to working conditions with similar fluid physical properties.

Keywords: oil–water two-phase flow; inclined inverted U-shaped pipe; retained oil layer; critical velocity



Academic Editor: Krzysztof Rogowski

Received: 22 June 2026

Revised: 9 July 2026

Accepted: 15 July 2026

Published: 17 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](#)[Attribution \(CC BY\) license](#).

1. Introduction

Mobile pipelines are pipeline systems consisting of pipes, mobile pumps, valves, metering instruments, and other components connected by detachable joints, and are mainly used for refined oil transportation. They are laid directly on ground surfaces and are characterized by rapid deployment and dismantling, as well as high operational flexibility. Before dismantling after oil transportation operations, or during pipeline maintenance, the oil remaining in the pipeline must be evacuated and recovered into oil tanks or oil tank trucks. Water-driven oil evacuation is a commonly used method for removing residual oil from pipelines. In this process, water is injected into the pipeline using a mobile pump, thereby progressively displacing the oil out of the pipe. This method is widely adopted because it can directly utilize existing oil transportation equipment and offers a simple procedure, rapid operation, low oil-vapor losses, and high safety.

During pipeline deployment, when a road crossing is required, a bridge-type crossing device is typically used to avoid obstructing vehicle traffic, as shown in Figure 1. The device is assembled from straight pipes, elbows, tees, and other components. Its inclination angle relative to the ground can be adjusted using support rods and pulleys, forming an inclined inverted U-shaped structure. However, recent field operations involving water-driven oil evacuation have shown that, even after the evacuation process was completed according to the prescribed procedures and operating parameters, a large amount of residual oil remained in the bridge-type crossing device during pipeline dismantling. This reduced the efficiency of pipeline dismantling and caused environmental contamination around the pipeline deployment area. Therefore, it is necessary to investigate the oil–water two-phase flow characteristics during water-driven oil evacuation in this special inclined inverted U-shaped pipeline configuration, so as to improve residual oil evacuation efficiency and provide theoretical support for water-driven oil evacuation in mobile pipelines.



Figure 1. Bridge-type crossing device.

At present, relatively systematic studies have been conducted on two-phase flow and interphase displacement in circular pipes. Among them, studies involving horizontal and inclined pipes are mainly associated with fixed oil pipelines, where a common engineering problem is pipeline corrosion caused by water accumulation in low-lying sections after shutdown. Existing studies have mainly focused on the mechanisms of water entrainment by oil flow, critical water-carrying velocity, phase-interface morphology, water holdup, and the effects of parameters such as inclination angle on the initiation and removal of accumulated water [1–17]. Magnini et al. [11] numerically investigated the displacement behavior of retained water at the horizontal-to-upward-inclined elbow of an undulating pipeline by diesel flow, and established a predictive model for the drift velocity of the water phase in the upward-inclined pipe. Xu et al. [15] studied the flow characteristics of oil carrying accumulated water in refined oil pipelines through experiments and numerical simulations. They found that the flow parameters of accumulated water were related to superficial oil velocity, dimensionless water-phase height, inclination angle, and other parameters, among which superficial oil velocity had the most significant influence. For two-phase flow in vertical pipes, existing studies mainly focus on vertical wellbores during oilfield production [18–24]. Liu et al. [18] proposed a new critical criterion for liquid loading in vertical wellbores based on liquid-film motion and flow-pattern classification and developed a more accurate liquid-loading prediction model by combining it with nodal analysis. Szpunar T [22] compared different methods for calculating critical production rates in vertical and horizontal wells, and proposed a simplified formula based on the bottomhole pressure–flow rate relationship to approximately evaluate the critical flow rate required to prevent water intrusion into the wellbore.

The bridge-type crossing device has an inclined inverted U-shaped structure, and the water-driven oil evacuation process is essentially an unsteady displacement flow in which

a heavy phase displaces a light phase. This process differs from the “light phase carrying a heavy phase” problem of oil flow entraining water in fixed oil pipelines and also differs from the axial mixed oil–water flow under co-transport conditions in oilfield wellbores. A full set of bridge crossing pipeline with a total length of 18 m and an inner diameter of 150 mm has an overall internal volume of approximately 318.1 L. Under most water-driven evacuation conditions, around 1/10 to 1/8 of this volume (roughly 31.8–39.8 L) forms trapped residual oil that cannot be completely flushed out. Although the absolute volume of retained oil is not enormous, it drastically reduces the recovery speed of mobile pipelines. Moreover, the accumulated residual oil creates potential soil and water contamination risks if leakage takes place during pipeline dismantling and storage.

Therefore, although existing studies on oil–water two-phase flow in horizontal pipes, inclined pipes, and vertical wellbores provide useful references for analyzing flow patterns, interfacial stability, and interphase slip, they cannot directly explain the oil–water two-phase flow characteristics in pipelines with this special convex inverted U geometry. Most previous works focus on concave low-lying pipe sections and oil-driven water flow, which differs fundamentally from the water-driven oil evacuation process in this inverted U-shaped pipeline. This work fills the research gap of residual oil retention in inverted U-shaped mobile pipelines, clarifies the coupled retention effects of vortex, internal recirculation and adverse pressure gradient, and provides direct operational guidance for on-site pipeline evacuation. Accordingly, this study combines theoretical analysis, numerical simulation, and experimental validation to investigate the flow characteristics of water-driven oil evacuation in inclined inverted U-shaped mobile pipelines. The aim is to reveal the mechanisms of oil–water displacement, interface evolution, and residual oil retention, thereby providing a theoretical basis for optimizing the water-driven oil evacuation process in mobile pipelines.

2. Mathematical Model

Because significant oil–water interfacial deformation, breakup, and coalescence occur in the pipeline, and the slip velocity between the two phases is relatively large, the VOF model was adopted as the primary multiphase-flow model to describe this process. To accurately capture the complex free-surface flow and interfacial-tension effects during water-driven oil evacuation, the CSF model was coupled with the VOF model to represent interfacial tension. Meanwhile, considering the strong curvature, adverse pressure gradient, and possible flow separation in the inclined inverted U-shaped pipe, the SST $k-\omega$ model was used for turbulence closure. The governing equations of these models are described below.

2.1. Governing Equations of the VOF Model

The water-driven oil evacuation process in the inclined inverted U-shaped pipe involves the motion of a distinct oil–water interface and includes complex flow patterns such as stratified flow and slug flow. The VOF model solves a single momentum equation and tracks the volume fraction of each fluid phase, enabling it to effectively handle two-phase flow problems with a distinct phase interface. In addition, it offers higher computational efficiency than interface-tracking methods such as the Level-Set method. The governing equations are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \left[\mu \left(\nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right] + \rho \mathbf{g} + \mathbf{F}_\sigma \quad (2)$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = 0 \quad (3)$$

where α is the phase volume fraction, ρ is the density, t is time, $\mathbf{u}$ is the velocity vector, ∇ is the gradient operator, p is pressure, μ is the dynamic viscosity of the fluid, $\mathbf{g}$ is the gravitational acceleration, and $\mathbf{F}_\sigma$ is the interfacial-tension source term.

2.2. SST k – ω Turbulence Model

In the elbow and downward-inclined section of the inverted U-shaped pipe, the flow is jointly affected by gravity and centrifugal force, resulting in a complex flow-field structure. The SST k – ω model accounts for the transport of turbulent shear stress and limits the overprediction of turbulent viscosity under adverse pressure gradients. This capability is essential for simulating possible flow separation and reattachment near the elbow and enables more accurate prediction of the formation location and thickness of the retained oil layer. Its transport equations are given as follows [25]:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{u} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \beta^* \rho \omega k \quad (4)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \nabla \cdot (\rho \mathbf{u} \omega) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \nabla \omega \right] + \varphi_1 \frac{\omega}{k} P_k - \varphi_2 \rho \omega^2 \quad (5)$$

$$\mu_t = \frac{\rho \alpha_1 k}{\max(\alpha_1 \omega, F_2)} \quad (6)$$

where P_k is the production term of turbulent kinetic energy, α_1 , φ_1 , φ_2 , β^* , σ_k , σ_ω are model constants, and F_2 is the blending function.

2.3. CSF Model

In inclined pipelines or under low-flow-rate conditions, interfacial tension is a key factor governing the stability of the oil–water interface and the formation of retained oil layers. This effect is particularly important near the elbow of the inverted U-shaped pipe, where interfacial tension directly influences oil-phase stripping and entrainment. The CSF model represents interfacial tension as a volumetric force source term in the momentum equation. It can be naturally coupled with the VOF method and can accurately simulate flow-field variations induced by capillary forces. The related equations are as follows:

$$\kappa = -\nabla \cdot \left(\frac{\nabla \alpha}{|\nabla \alpha|} \right) \quad (7)$$

$$\mathbf{F}_\sigma = \sigma \kappa \frac{\nabla \alpha}{|\nabla \alpha|} \delta_s \quad (8)$$

where σ is the interfacial-tension coefficient and δ_s is the interfacial Dirac delta function.

3. Methodology

ANSYS Fluent 2024 R1 was used to numerically simulate this operating condition, and the characteristics of water-driven oil evacuation in the inclined inverted U-shaped pipeline were analyzed.

3.1. Computational Domain, Initial Conditions, and Boundary Conditions

Based on the bridge-type configuration of a mobile pipeline crossing a road, and considering the variation in inclination angle during bridge construction, a geometric model was established, as shown in Figure 2. The corresponding geometric dimensions are indicated in the figure.

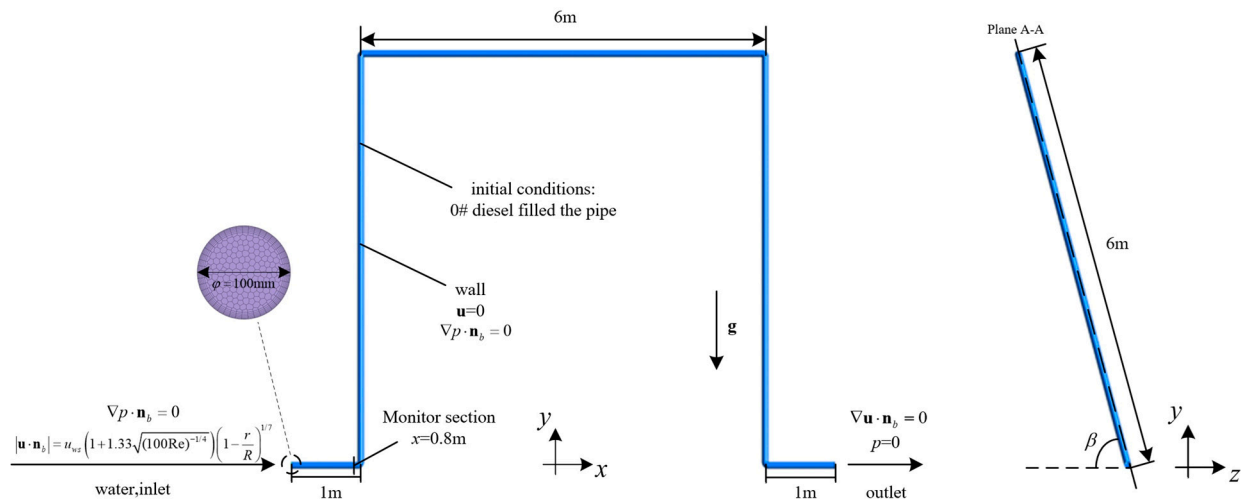


Figure 2. Computational domain, initial conditions, and boundary conditions.

A three-dimensional Cartesian coordinate system was established with reference to the pipeline fluid inlet. The origin of the coordinate system is located at the center of the upstream inlet cross-section. The x -axis coincides with the line connecting the pipeline centerline along the downstream flow passage, with its positive direction pointing along the mainstream flow direction. The positive y -axis is vertically upward and opposite to the direction of gravity acting on the fluid in the pipeline. The z -axis is perpendicular to the x - y plane, with its positive direction pointing toward the side not occupied by the pipeline. During bridge-type pipeline installation, the inclination angle β relative to the ground is typically within the range of 30–75°. Therefore, during geometric model construction, the inclination angle between the bridge-type pipeline and the ground was adjusted by rotating the geometric model about the z -axis.

Water was set as the primary phase, and oil was set as the secondary phase. At the initial moment, the pipeline was filled with No. 0 diesel. The model inlet was defined as a velocity inlet. Since the water phase had already reached a fully developed turbulent state when the actual water-driven oil evacuation reached the bridge-type section, the Blasius one-seventh power-law distribution was used to describe the fully developed turbulent inlet profile. The model outlet was set as a pressure outlet with a gauge pressure of 0. At the wall, a no-slip wall boundary condition was applied, where $\mathbf{n}_b$ and $\mathbf{t}_b$ denote the unit normal vector and unit tangential vector at the wall, respectively. Additionally, wall wettability was characterized by the static contact angle boundary condition embedded in the VOF model. The static water contact angles of two pipe materials were experimentally measured in advance: the plexiglass pipe used in the visualization experiment has a static water contact angle of 120°, presenting weak oleophilic wettability; the steel pipe applied in actual mobile pipeline engineering has a static water contact angle of 140°. In numerical simulations, the corresponding contact angle values were adopted for different sets of cases: the validation cases matched the 120° contact angle of the plexiglass experimental pipe, while the full-scale engineering simulation cases adopted the 140° contact angle of the steel pipe. This setting ensures strict consistency of wall boundary conditions between the numerical model and the corresponding physical scenario.

To ensure consistency between the simulation and actual conditions, liquid water and No. 0 diesel were selected as the fluid in the pipe. The effect of temperature was neglected. The densities and viscosities of the oil and water were treated as constants and were set according to experimentally measured values at 25 °C. The interfacial tension between the two phases was determined with reference to Ref. [15], the specific parameters are listed in Table 1.

Table 1. Physical property parameter settings.

Parameter	Water	No. 0 Diesel
Density, ρ (kg/m ³)	998.2	833.5
Viscosity, μ (mPa·s)	1.003	3.500
Interfacial tension, σ (mN/m)	18.2	

To verify the rationality of adopting the SST $k-\omega$ turbulence model for all operating conditions, validation was conducted from two aspects: flow regime determination and near-wall grid matching. First, the Reynolds number of all operating conditions was estimated based on the inlet superficial water velocity and pipe geometric parameters. The Reynolds number for pipe flow is defined as: $Re = \rho u_{ws} D / \mu$. Calculation results show that the Reynolds number of all working conditions in this paper ranges from 12,500 to 121,600, which is all well above the critical Reynolds number of laminar flow in circular pipes ($Re = 2300$), indicating that all cases are in the fully developed turbulent regime. Even at the lowest superficial water velocity, the flow still exhibits significant turbulent fluctuation characteristics. Meanwhile, centrifugal disturbance at the elbow and shear effect at the oil–water interface further enhance turbulent mixing, and no laminarization or transition problem occurs. Therefore, the adoption of the turbulence model has a solid flow regime basis.

3.2. Mesh Generation and Grid-Independence Verification

To accurately capture the oil–water interfacial phenomena while improving computational efficiency, the Poly-Hexcore meshing scheme was adopted. The generated mesh is shown in the upper-left corner of Figure 2. The operating condition with an inclination angle of $\beta = 75^\circ$ and a water-phase inlet superficial velocity of $u_{ws} = 0.815$ m/s was selected for the grid-independence test. Four different mesh schemes were generated, with total cell numbers of 0.88 million (scheme a), 1.25 million (scheme b), 1.65 million (scheme c), and 1.98 million (scheme d), respectively.

The grid independence verification is carried out by comparing two evaluation indicators: the velocity distribution along the pipe centerline at the monitoring cross-section ($x = 0.8$ m), and the residual oil volume fraction V_r , defined as the ratio of residual oil volume to the total pipe internal volume at $t = 10$ s. The velocity profiles at the monitoring cross-section obtained from each mesh scheme are plotted in Figure 3, while the corresponding residual oil volume fraction values are summarized in Table 2. As observed in Figure 3, the centerline velocity at the monitoring cross-section generally presents a parabolic distribution characteristic of fully developed turbulent flow. Scheme a shows an obviously large velocity deviation at the pipe center compared with the other three refined mesh schemes, which means this coarse mesh should be discarded. As the number of mesh cells increases gradually, the velocity distribution converges to a stable profile. According to the quantitative data in Table 2, the relative deviation of residual oil volume fraction between Scheme a and the finest reference Scheme d reaches 7.8%, indicating insufficient computational accuracy. From Scheme b to Scheme d, the relative deviation of V_r only decreases slightly from 1.4% to 0.5%. This demonstrates that the core oil evacuation characteristic indicator has basically achieved grid convergence after the mesh is refined to 1.25 million cells. Taking both computational cost and numerical accuracy into comprehensive consideration, Mesh Scheme b is selected as the final discretization scheme for all subsequent numerical simulations in this work.

For near-wall flow simulation, the automatic near-wall treatment built into the SST $k-\omega$ model was adopted. This scheme can smoothly transition between near-wall direct integration and wall function according to the dimensionless wall distance y^+ of the near-

wall grid, taking both calculation accuracy and numerical stability into account. Combined with the near-wall boundary layer encryption strategy of the Poly-Hexcore mesh, under the typical working condition ($\beta = 75^\circ$, $u_{ws} = 0.215$ m/s, $D = 100$ mm), the y^+ value of the first layer of grid near the wall is distributed in the range of 0.7–2.3, with a cross-sectional average y^+ of about 1.1. This meets the accuracy requirement of near-wall resolution for the SST $k-\omega$ model, and can accurately capture the velocity gradient and shear stress distribution in the wall boundary layer, providing a reliable near-wall flow field basis for the simulation of residual oil layer adhesion, stripping and interfacial shear.

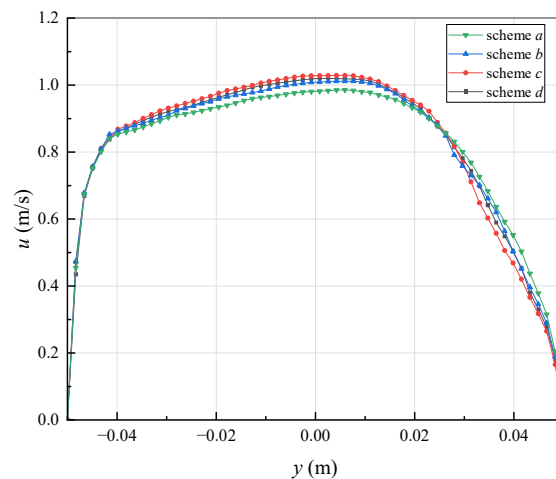


Figure 3. Grid-Independence Verification.

Table 2. Residual Oil Volume Fraction in Pipeline at $t = 10$ s.

Mesh Scheme	V_r	Relative Deviation (Referenced to Scheme d)
a	0.192	7.2%
b	0.204	1.4%
c	0.206	0.5%
d	0.207	-

In addition, a time-step convergence study was carried out to ensure that the time-step setup does not contaminate the numerical results. A subcritical working condition with inclination angle $\beta = 75^\circ$ and inlet superficial water velocity $u_{ws} = 0.215$ m/s was selected for verification. Under this condition, the oil–water interface undergoes mild deformation while stable oil accumulation persists; prominent oil-front vortices and internal recirculation can be observed, and the overall oil evacuation process lasts for a long duration. Numerical diffusion induced by improper time steps tends to accumulate and amplify throughout the simulation, which makes the verification results conservative and representative for all calculation cases adopted in this work. Three groups of fixed time-step schemes were set up, namely 0.002 s, 0.005 s, and 0.010 s, corresponding to the maximum local Courant numbers near the oil–water interface of approximately 0.2, 0.5 and 1.0, covering the critical stability range of the VOF interface capturing method. The residual oil volume fraction V_r after the trapped oil layer reaches a stable morphology at $t = 150$ s was selected as the convergence evaluation indicator, and the comparison results are summarized in Table 3.

As shown in Table 3, the predicted residual oil volume fraction gradually converges as the time step decreases. For the time step of 0.01 s, the relative deviation from the reference case reaches 9.9%, accompanied by severe numerical diffusion at the oil–water interface, which significantly overestimates the trapped oil volume and fails to meet the required calculation accuracy; this scheme is therefore discarded. When the time step is reduced

to 0.005 s, the relative deviation compared with the fine reference step of 0.002 s drops to only 3.0%. The transient evolution curves of V_r maintain consistent trends and close numerical values throughout the simulation, indicating that this time step can accurately capture interface propagation, vortex development and the stable morphology of trapped oil layers. Balancing numerical precision and computational efficiency, a fixed time step of $\Delta t = 0.005$ s is adopted for all working conditions in this paper. The discretization schemes and solution algorithms used in the simulations are listed in Table 4.

Table 3. Residual Oil Volume Fraction in Pipeline at $t = 150$ s.

Time Step Δt (s)	Maximum Interfacial Courant Number	V_r	Relative Deviation (Referenced to $t = 150$ s)
0.002	≤ 0.2	0.126	-
0.005	≤ 0.5	0.130	3.0%
0.010	≤ 1.0	0.143	9.9%

Table 4. Solution method of simulation.

Spatial Discrete Method	Gradient Pressure Body Force Momentum Volume fraction Turbulent Kinetic Energy Specific Turbulent Dissipation Rate	Least Squares Cell-Based Weighted Second Order Upwind Geo-Reconstruct Second Order Upwind Second Order Upwind
Solver algorithm		PISO
Time step		0.005 s
Maximum number of iterations		50

3.3. Model Validation

To validate the predictive reliability of the model for the water-driven oil evacuation process in an actual inverted U-shaped inclined pipeline, the model was verified based on indoor visualization experiments. An experimental facility with a pipe diameter of $D = 50$ mm was constructed, and the corresponding model dimensions were reduced according to geometric similarity. Xu et al. [15] investigated the process of oil displacing accumulated water in inclined pipelines, which corresponds to gravity-dominated two-phase displacement where the light phase drives the heavy phase. The present study focuses on water-driven oil evacuation, i.e., the heavy-phase water displaces light-phase diesel. These two flow scenarios share highly consistent core flow mechanisms, and the relative motion between the two immiscible liquids is jointly governed by inertial force and gravity. Therefore, the Froude scaling method proposed in Ref. [15] is followed in this work.

The experimental system mainly consisted of an oil tank, a water tank, a pumping system, flowmeters, pressure sensors, a three-way valve, a transparent inverted U-shaped pipe section, a high-speed camera, and an oil–water separation and recovery unit, as shown in Figures 4 and 5. Before each experiment, the transparent inverted U-shaped pipe section was first filled with oil using the oil pump, and the residual gas in the pipe was removed through the vent to ensure that the pipeline was initially filled with a single oil phase. Subsequently, the water pump was started, and water was injected from the pipeline inlet at a prescribed inlet superficial water velocity. The evolution of the oil–water interface during the water-driven oil displacement process was recorded using the high-speed camera, while the critical water superficial velocity required for complete oil purge-out was recorded using the flowmeter.

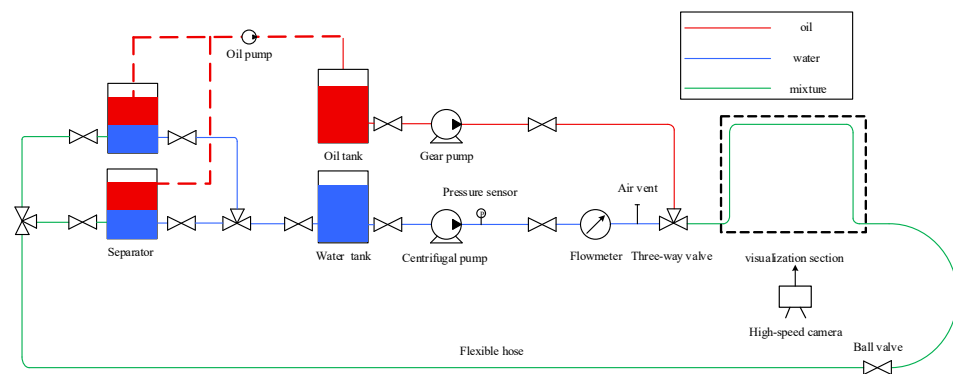


Figure 4. Schematic description of the experimental setup.



Figure 5. Experimental setup.

3.3.1. Validation of the Critical Superficial Water Velocity

Four typical inclination angles, $\beta = 30^\circ, 45^\circ, 60^\circ$ and 75° , were selected for comparison between the experimental and numerical results. The pipe diameter of the experimental facility was $D_m = 50$ mm, while the actual pipe diameters were $D_p = 100$ mm and 150 mm. According to the Froude number similarity criterion, the critical water superficial velocities at different scales are calculated as: $u_{ws-crit,p} = u_{ws-crit,m} \sqrt{D_p/D_m}$.

The critical water superficial velocity for complete purge-out, $u_{ws-crit}$, was used as the validation parameter. The converted experimental results and numerical simulation results are listed in Table 5.

Table 5. Model validation results for the critical superficial water velocity.

β ($^\circ$)	$u_{ws-crit}$ Experimental Value (m/s)	Converted Value for 100 mm Pipe (m/s)	Simulated Value for 100 mm Pipe (m/s)	Error (%)	Converted Value for 150 mm Pipe (m/s)	Simulated Value for 150 mm Pipe (m/s)	Error (%)
30	0.240	0.339	0.355	4.7	0.416	0.442	6.3
45	0.295	0.417	0.440	5.5	0.511	0.548	7.2
60	0.385	0.544	0.585	7.5	0.667	0.715	7.2
75	0.500	0.707	0.758	7.2	0.866	0.939	8.4

Although viscous force and interfacial tension simultaneously exist in the oil–water two-phase flow inside the pipeline, the core target parameter of the scaling conversion in this paper is the critical superficial water velocity for complete oil removal. This critical threshold is determined by the gravity stratification effect and the inertial momentum of water flow, while viscous force and capillary tension only play secondary regulatory roles within the range of fluid properties, pipe diameters and inclination angles adopted in this study. The mismatches of Reynolds number and Weber number between the scaled model and full-scale prototype cannot reverse the monotonic variation trend of critical velocity

with geometric parameters. The relative errors between converted critical velocities and numerical simulation results are all less than 10%, which meets the accuracy requirement of engineering calculation.

In addition, the applicable scope of the single Froude similarity criterion is clearly stated that the scaling method is only valid for the system of No. 0 diesel and clean water under ambient temperature. For crude oil with ultra-high viscosity or microscale pipelines where capillary effects are prominent, simultaneous similarity of Froude, Reynolds and Weber numbers should be considered, which will be further investigated in our future research.

3.3.2. Validation of Flow Patterns

In addition to the critical superficial water velocity as a macro-scale engineering indicator, the accuracy of the numerical model in reproducing transient interface evolution and flow pattern transition was further verified against visualization experiments. The comparison focuses on the oil–water distribution in the downward-inclined section under the same inclination angle. The flow time is counted from the moment when the waterfront reaches the starting point of the downward-inclined section, ensuring a consistent time benchmark between simulation and experiment. For the subgraphs, red stands for oil and blue stands for water in the upper numerical simulation results, while yellow represents oil and white represents water in the lower experimental photographs. The comparison of oil–water two-phase distribution observed at the upstream of section A-A under different operating conditions is shown in Figure 6.

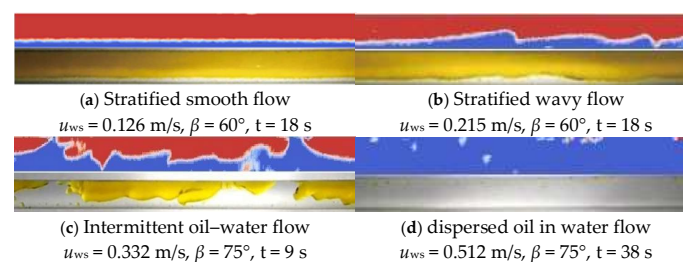


Figure 6. Validation of Flow Patterns and Interface Morphology.

Four typical flow patterns from low to high superficial water velocity are presented and compared:

The above comparison demonstrates that the established numerical model can not only accurately predict the critical evacuation velocity at the macro level, but also reliably reproduce interface deformation, flow pattern transition and oil phase entrainment characteristics at the mesoscopic level. This verifies the fidelity of the transient flow field simulation, and provides a solid numerical basis for the subsequent mechanistic analysis of vortex structures, internal recirculation and adverse pressure gradient effects.

4. Results and Discussion

4.1. Time-Series Analysis

Water-driven oil evacuation in an inclined inverted U-shaped pipe is a typical transient flow process. To systematically investigate this transient behavior, a time-series analysis was performed. According to the geometric position reached by the water front in the pipe, the overall evacuation process can be divided into three stages. The first stage corresponds to the flow before the water phase reaches the highest point of the upward-inclined section. The second stage refers to the flow of the water phase in the second horizontal section, while the third stage describes the flow before the water phase reaches the outlet.

As shown in Figure 7, the contours present the oil–water volume fraction distribution on a centerline section of the pipe viewed from the front. In the contours, red represents the oil phase and blue represents the water phase. This stage corresponds to the first stage of the evacuation process. To clearly illustrate the flow characteristics in this stage, a relatively low superficial water velocity of $u_{ws} = 0.126$ m/s at which the inlet water flow remains turbulent, was selected for analysis, with an inclination angle of $\beta = 75^\circ$.

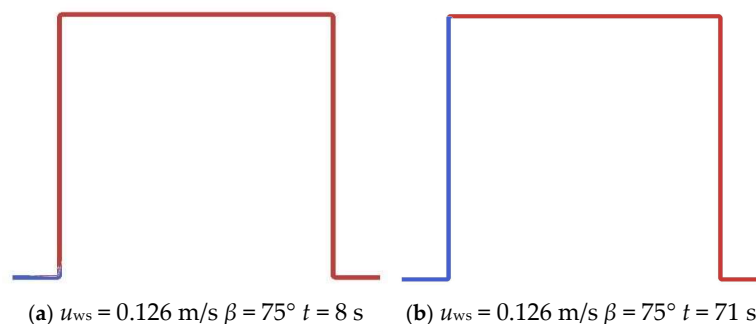


Figure 7. First stage of the evacuation process.

During this stage, it is observed that, regardless of variations in inclination angle and inlet superficial water velocity, the water phase can fully displace the oil phase from both the first horizontal section and the upward-inclined section, provided that the process lasts long enough. Different operating conditions mainly affect the duration of this stage. This behavior is primarily attributed to the density difference between the oil and water phases. Since water is denser than oil, the oil phase tends to float above the water phase in the upward-inclined section. Driven by the displacement pressure of the incoming water, the water phase advances along the lower part of the pipe and gradually squeezes the oil phase in the upper region, thereby achieving effective oil displacement in the first horizontal section and the upward-inclined section.

Figure 8 shows the second stage of the evacuation process. In this stage, the water front leaves the upward-inclined section and enters the second horizontal section, where it advances at a relatively stable velocity. Since the inclination effect is absent in this section, the evacuation performance is mainly governed by the superficial water velocity. It is observed that, at a relatively high superficial water velocity, effective displacement can be achieved in the horizontal pipe section. However, at a low superficial water velocity, a thin oil layer remains in the upper part of the horizontal pipe and cannot be completely evacuated. In addition, at the elbow connecting the second horizontal section and the downward-inclined section, the water phase suddenly loses the support provided by the lower pipe wall, leading to the formation of a water slug. As a result, an oil-accumulation region develops in the upper part of the elbow.

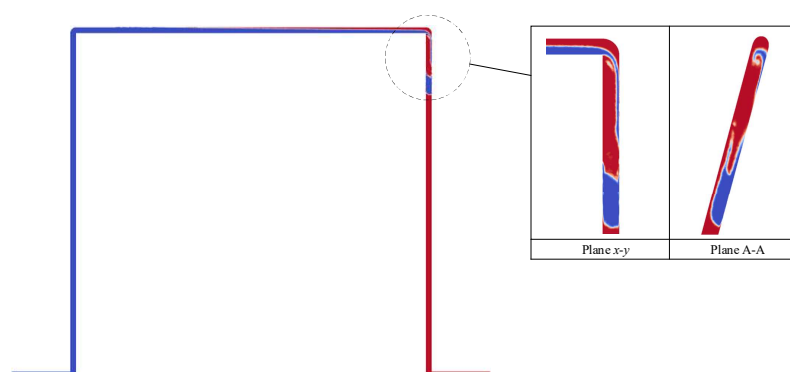


Figure 8. Second stage of the evacuation process.

Figure 9 presents the case with $u_{ws} = 0.126 \text{ m/s}$ $\beta = 75^\circ$ $t = 160 \text{ s}$, and $u_{ws} = 0.541 \text{ m/s}$ $\beta = 45^\circ$ $t = 42 \text{ s}$, which shows the third stage of the evacuation process. In this stage, the waterfront reaches the downward-inclined section, where the flow behavior becomes the most complex. It is observed that the final oil evacuation performance differs significantly under different operating conditions.

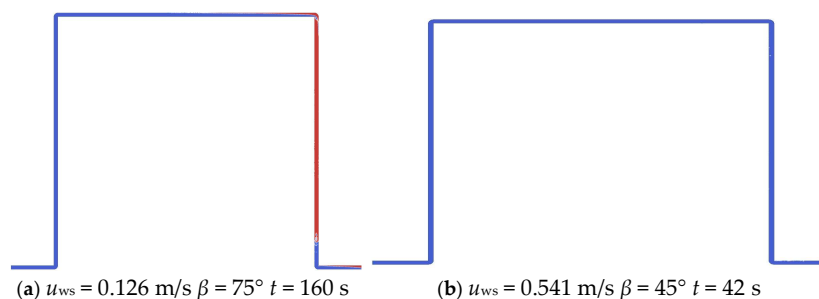


Figure 9. Third stage of the evacuation process.

Under conditions of low inlet superficial water velocity and large inclination angle, a retained oil layer that cannot be evacuated from the pipe is observed. This retained oil layer is mainly distributed in the upper region of the pipe, and complete evacuation cannot be achieved regardless of how long the process continues. In contrast, under conditions of high inlet superficial water velocity and small inclination angle, the water phase can cover the pipe cross-section more uniformly and continue to advance, eventually evacuating almost all the oil phase in the pipe, with no obvious retained oil layer.

4.2. Effect of Inlet Superficial Water Velocity

The oil evacuation process in the inclined inverted U-shaped pipe was analyzed for cases with an inclination angle of 75° and inlet superficial water velocities ranging from 0.126 m/s to 0.815 m/s . A point-line plot with t as the horizontal axis and V_r as the vertical axis is shown in Figure 10.

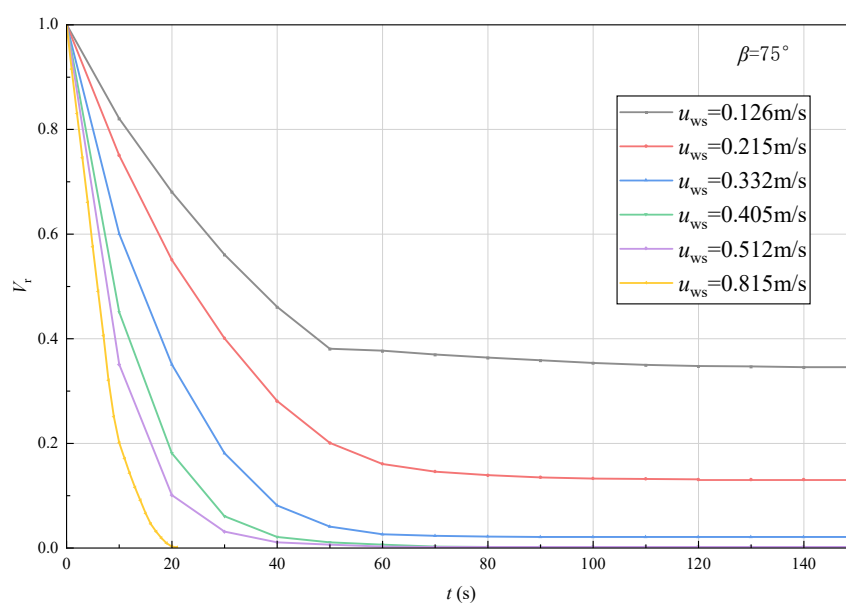


Figure 10. Variation in residual oil volume fraction in the pipe with time at different inlet superficial velocities for $\beta = 75^\circ$.

As can be seen from the figure, some curves exhibit distinct inflection points. This is because, in the early stage of evacuation, the pipe outlet contains pure oil. When the waterfront reaches the outlet boundary, the outlet condition changes from pure oil to an oil–water mixture, resulting in a reduced evacuation rate in the later stage. Before the inflection point, the residual oil volume fraction in the pipe is negatively correlated with time, and a higher inlet superficial water velocity corresponds to a larger linear slope. After the inflection point, under low-velocity conditions, the curve slope decreases to nearly zero, indicating the presence of a retained oil layer that cannot be completely evacuated by the water phase. In contrast, as the inlet superficial water velocity increases, the curve becomes steeper and the evacuation time shortens, indicating an increased evacuation rate and the absence of a retained oil layer in the pipe.

Since the presence of a retained oil layer significantly affects the evacuation performance, it is necessary to further analyze its morphology, formation mechanism, and flow characteristics in order to improve the evacuation efficiency. By examining the oil–water volume-fraction contours, it is found that the retained oil layer mainly forms and persists in the downward-inclined section of the inverted U-shaped inclined pipe at relatively low inlet superficial water velocities. Therefore, cases with $\beta = 45^\circ$, $u_{ws} = 0.126 \text{ m/s} \sim 0.405 \text{ m/s}$ and $t = 150 \text{ s}$ are selected for analysis. The oil–water distribution contours in the downward-inclined section of the inclined inverted U-shaped pipe under different inlet superficial water velocities are shown in Figure 11.

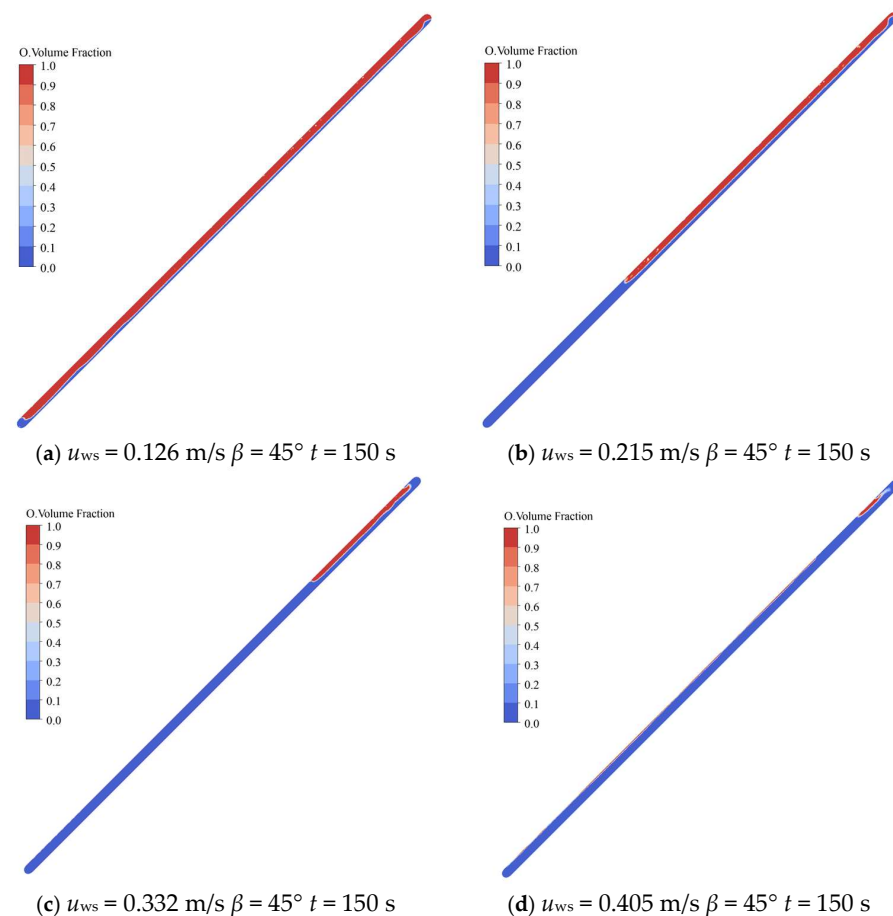


Figure 11. Oil–water volume-fraction contours of the retained oil layer at $\beta = 45^\circ$ and $t = 150 \text{ s}$.

As shown in Figure 11, when $\beta = 45^\circ$ and $u_{ws} = 0.126 \text{ m/s} \sim 0.405 \text{ m/s}$, obvious retained oil layers can be observed in the pipe, but their morphologies differ with inlet superficial water velocity. The oil layer in Figure 11a occupies almost the entire downward-inclined

section, with a large thickness and long axial extent. As the inlet superficial water velocity increases, the oil-layer thickness gradually decreases, its length becomes shorter, and its spatial position continuously shifts upstream. When $u_{ws} = 0.405$ m/s, the retained oil layer has gradually evolved into small retained oil droplets or oil clusters.

The oil–water volume-fraction contours and velocity vector plots in the downward-inclined section under the condition of $u_{ws} = 0.215$ m/s, $\beta = 60^\circ$ and $t = 150$ s are shown in Figure 12. In the velocity vector plot, colors closer to red indicate higher velocity, while colors closer to blue indicate lower velocity, and the arrows indicate the liquid flow direction.

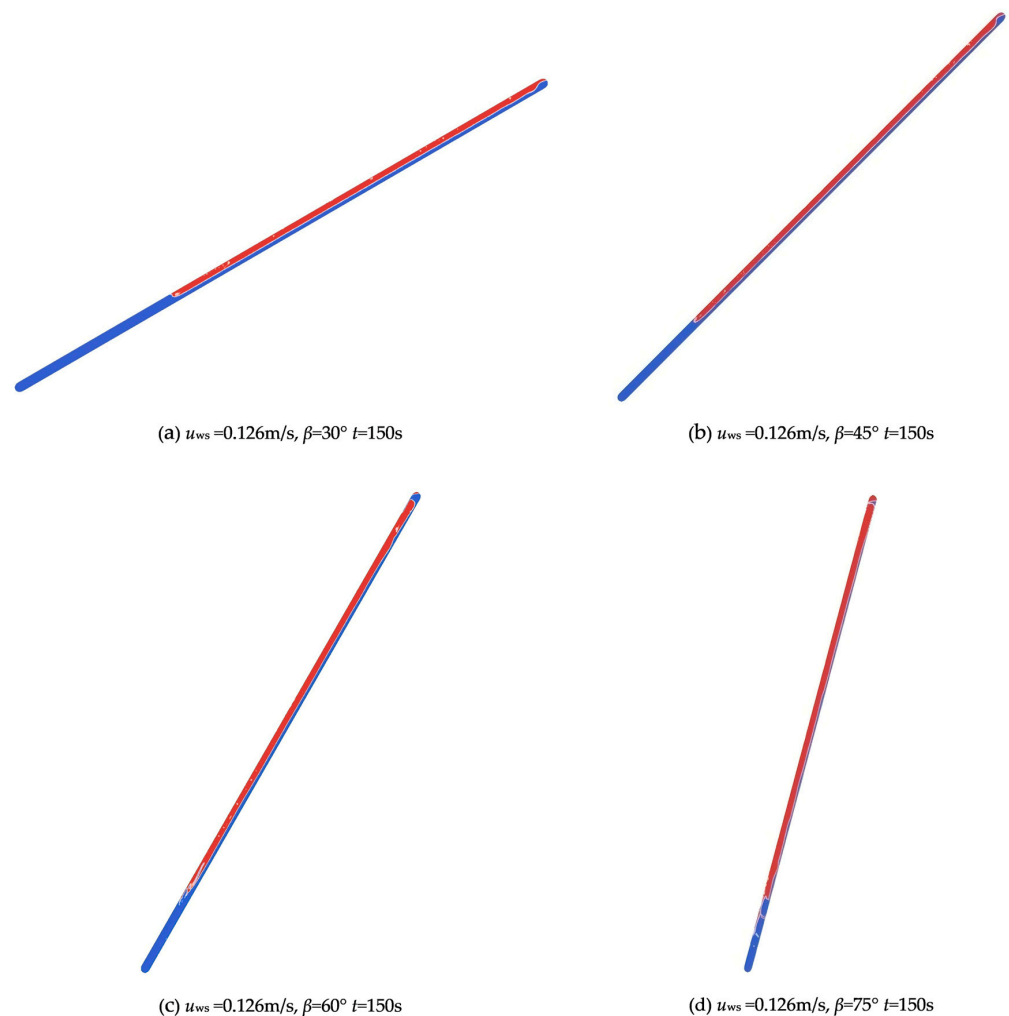


Figure 12. Comparison of oil–water volume-fraction contours and velocity vector plots in the downward-inclined section at $u_{ws} = 0.215$ m/s, $\beta = 60^\circ$, $t = 150$ s.

Because diesel has a lower density than water, the oil phase tends to occupy the upper part of the pipe, whereas the water phase advances along the lower part. During flow through the downward-inclined section, gravity accelerates the water phase. However, due to its higher viscosity and stronger adhesion to the pipe wall, the oil phase accelerates more slowly, resulting in obvious velocity slip in the downward-inclined section. This slip generates shear stress at the oil–water interface. Nevertheless, because the overall flow velocity is relatively low, the shear force is insufficient to destabilize the interface. As a result, a large amount of oil becomes trapped in the upper region of the downward-inclined section of the inclined inverted U-shaped pipe, forming a persistent retained oil layer that hinders the evacuation process.

As the inlet velocity increases, the kinetic energy of the water flow and the interfacial shear force increase significantly. The oil–water interface of the retained oil layer begins to fluctuate, and the water flow passage narrows. Under the action of the gravitational component, the water phase accelerates sharply, further increasing the shear force between the oil and water phases. The retained oil layer is then torn apart and entrained, forming a dispersed flow in which both water-in-oil and oil-in-water structures coexist. At this stage, the oil phase is efficiently carried out of the pipe by the high-speed water flow in the form of oil bubbles or droplets, leading to a significant reduction in the residual oil volume.

The oil–water volume-fraction contours overlaid with streamlines under the condition of $u_{ws} = 0.215$ m/s, $\beta = 60^\circ$ and $t = 150$ s are shown in Figure 13. In the background contours, red represents the oil phase and blue represents the water phase. Streamlines are colored according to local velocity magnitude; red corresponds to higher velocity magnitude, while blue represents lower velocity magnitude.

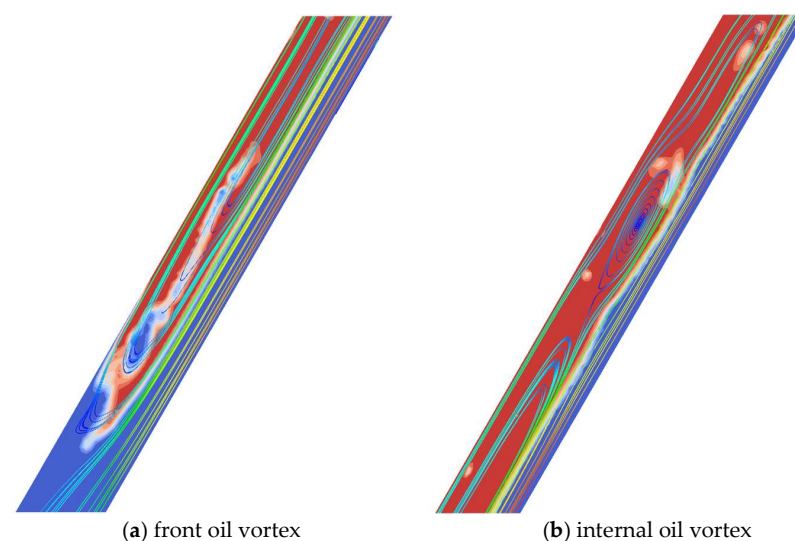


Figure 13. Superimposed oil–water volume-fraction contours and streamlines at $u_{ws} = 0.215$ m/s, $\beta = 60^\circ$, $t = 150$ s.

Figure 13a shows the front position of the retained oil layer near the outlet. A distinct vortex structure can be observed at the front of the retained oil layer, indicating that the oil-phase front tends to flow back upstream under the combined effects of wall shear stress, water-phase shear stress, net buoyancy, and interfacial tension. Consequently, under this operating condition, the oil layer contracts toward the upstream region of the pipe, and its morphology changes from a thin and elongated shape to a thicker and more compact structure.

As shown in Figure 13b, in addition to the vortex at the front of the oil–water interface, obvious vortex structures also exist inside the retained oil layer. This indicates that internal recirculation occurs within the oil layer, which further strengthens the retention of the oil phase.

Figure 14 shows the pressure distribution contours in the downward-inclined section under the condition of $u_{ws} = 0.332$ m/s, $\beta = 60^\circ$ and $t = 150$ s. In the pressure contours, red denotes the high-pressure region, while blue denotes the low-pressure region. It can be observed that the pressure generally increases from the upper part to the lower part of the downward-inclined pipe and reaches its maximum at the connection between the downward-inclined section and the elbow.

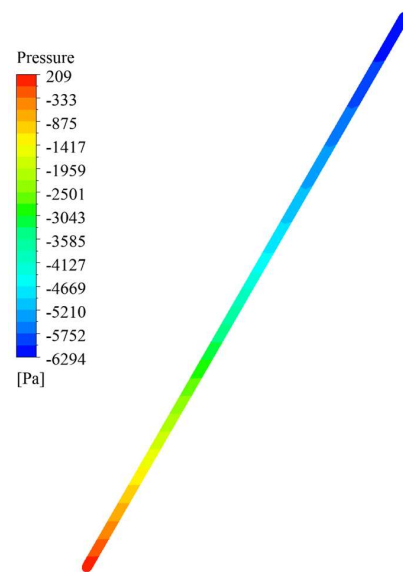


Figure 14. Pressure distribution contours at $u_{ws} = 0.332$ m/s, $\beta = 60^\circ$ and $t = 150$ s.

This indicates that an adverse pressure gradient exists during the water-displacing-oil evacuation process in the downward-inclined section, and the pressure-difference driving force plays a hindering role in the flow. Meanwhile, the upper region of the pipe exhibits negative pressure, causing the fluid at the lower end of the pipe to tend to flow upward, which further intensifies the formation of the retained oil layer.

It should be noted that wall wettability mainly affects the adhesion behavior of the thin oil film attached to the upper pipe wall. Within the pipe diameter and velocity range of this study, the contact angle difference between organic glass and steel pipe has limited influence on the overall critical evacuation velocity, and the deviation is within the experimental error range. A systematic sensitivity analysis of wall wettability will be carried out in follow-up research.

4.3. Effect of Pipe Inclination Angle

Variation in the pipe inclination angle changes the component of net buoyancy along the flow direction, thereby affecting the dynamic behavior of the oil–water two-phase flow in the pipe. In practical erection of floating bridge structures, the inclination angle is also an adjustable independent variable. Therefore, it is necessary to investigate the influence of inclination angle on the evacuation process.

Since the inclination angle β relative to the ground is generally between 30° and 75° during practical bridge-type crossing structure installation, four inclination angles, namely 30° , 45° , 60° , 75° , were selected for the numerical simulations. Figure 15 shows the oil–water two-phase volume-fraction contours at cross-section A–A under different inclination angles when the inlet superficial water velocity is 0.126 m/s and $t = 150$ s.

As shown in Figure 15, when the inlet superficial water velocity is lower than the critical water velocity, the morphology of the retained oil layer changes from thin and elongated to thick and compact as the inclination angle increases. This is because a larger inclination angle in the downward-inclined section amplifies the effect of net buoyancy. With increasing inclination angle, the oil phase accumulates more stably in the upper part of the pipe, while the water phase mainly flows along the lower part of the pipe. As a result, the shear-driven carrying capacity of the water phase acting on the upper oil layer becomes weaker, causing the retained oil layer to become thicker.

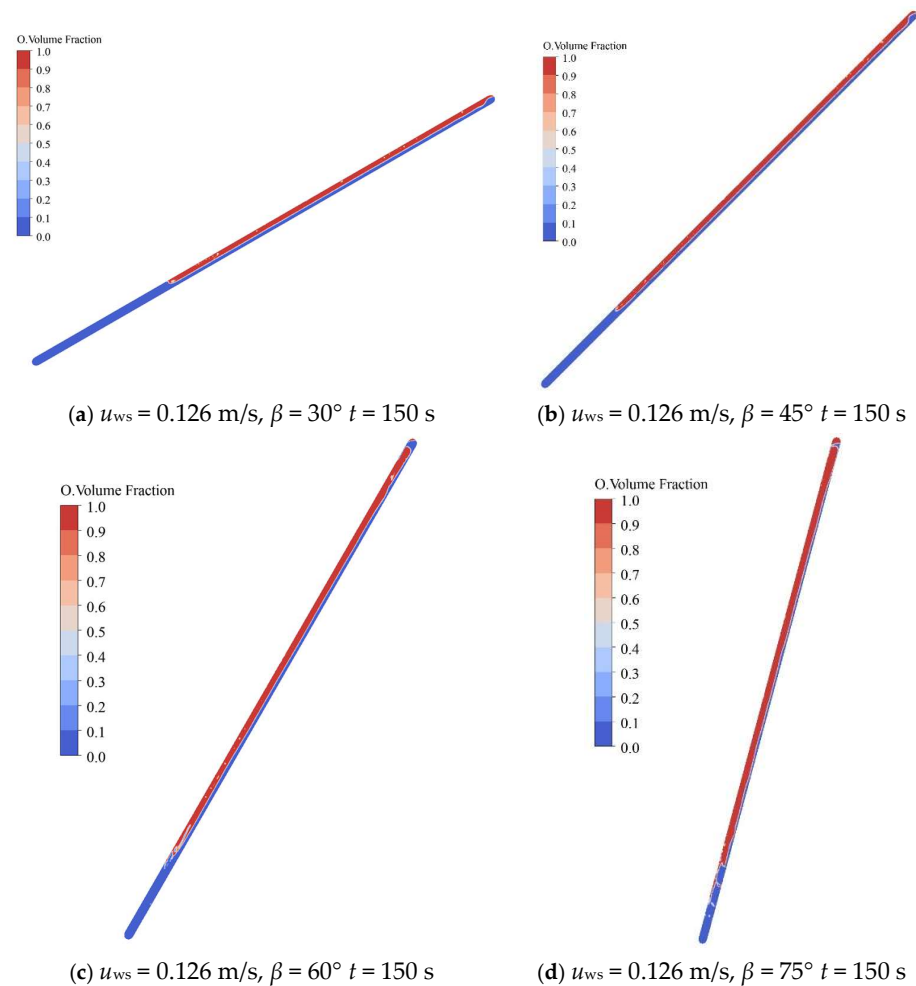


Figure 15. Oil–water volume fraction contours in the downward-inclined pipe under different inclination angles.

Conversely, when the inclination angle is smaller, the stability of the oil–water interface decreases, and the water phase more readily disturbs and entrains the oil phase, thereby reducing the volume of retained oil.

To further analyze the relationship between the inlet superficial water velocity and the critical velocity, the temporal variations in the residual oil volume fraction in the pipe under different inclination angles were plotted for inlet superficial water velocities of $u_{ws} = 0.126$ m/s and 0.815 m/s, as shown in Figure 16.

As shown in Figure 16a, when the inlet superficial water velocity is higher than the critical water velocity, increasing the pipe inclination angle shortens the time required for the water front to reach the computational boundary of the pipe, thereby reducing the total evacuation time. This indicates that a larger inclination angle accelerates the downstream migration of the oil layer under this condition.

In contrast, Figure 16b shows that when the inlet superficial water velocity is lower than the critical water velocity, increasing the pipe inclination angle leads to a higher residual oil volume fraction after the flow reaches equilibrium, indicating an increase in the total volume of retained oil. Therefore, under subcritical inlet water velocity conditions, increasing the pipe inclination angle weakens the efficiency of water-displacing-oil evacuation.

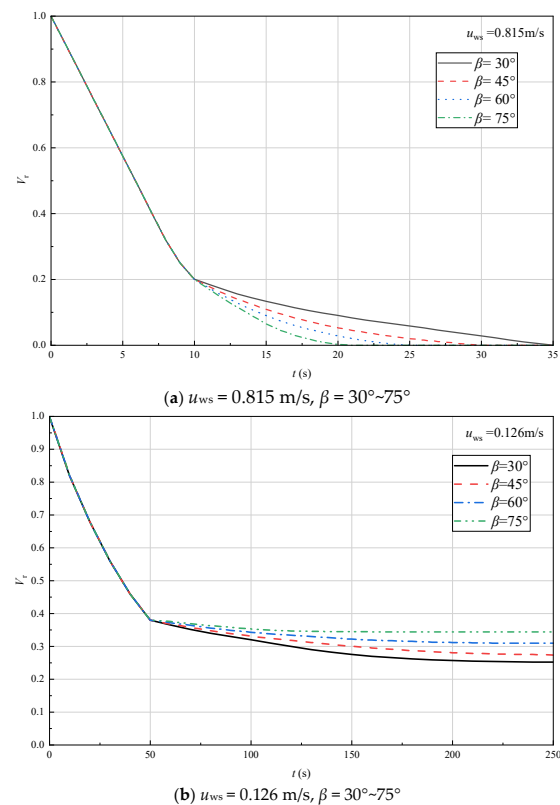


Figure 16. Temporal variation in residual oil volume fraction in the pipe under different inclination angles.

4.4. Effect of Pipe Diameter

In engineering applications of mobile pipelines, pipe diameter is a key geometric parameter determining the transport capacity. To investigate the influence mechanism of pipe diameter on the water-displacing-oil evacuation process in an inclined inverted U-shaped pipe, this section mainly compares two pipe diameters currently used in mobile pipelines, namely 100 mm and 150 mm.

The pipe inclination angle was kept constant at $\beta = 45^\circ$, and the inlet superficial water velocity was maintained at $u_{ws} = 0.425 \text{ m/s}$. Under a fixed inlet superficial velocity, the morphological evolution of the retained oil layer and the differences in evacuation efficiency for different pipe diameters were examined.

To ensure that the evacuation process was sufficiently developed, the flow fields at $t = 150 \text{ s}$ for different pipe diameters were selected for analysis. It was observed that as the pipe diameter increased, the morphology and distribution characteristics of the retained oil layer changed significantly. Figure 17 shows the temporal variation in the residual oil volume fraction in the pipe under different pipe diameters.

As shown in Figure 17, under the same inlet superficial water velocity of $u_{ws} = 0.425 \text{ m/s}$, the pipe diameter has a significant influence on the oil evacuation efficiency. For the pipe with $D = 100 \text{ mm}$, this velocity reaches the critical evacuation condition, and the interfacial shear force is sufficient to overcome the viscous resistance of the oil phase and the gravitational stratification effect. As the evacuation process proceeds, the residual oil volume fraction decreases approximately linearly and reaches zero at $t = 85 \text{ s}$, indicating that the oil phase in the pipe has been completely displaced and full evacuation is achieved.

However, for the larger-diameter pipe with $D = 150 \text{ mm}$, the enlarged flow cross-sectional area weakens the effective driving action on the oil phase under the same inlet condition, resulting in a significant reduction in the shear stress acting on the oil–water interface. The results show that although the initial evacuation rate is relatively high, about

32% of the oil phase still remains in the large-diameter pipe at $t = 85$ s. Subsequently, the residual oil fraction does not continue to decrease substantially, but enters a quasi-steady retention stage. During $t = 85$ s~150 s, the residual oil fraction decreases only slightly from 32% to 29%. This slight reduction is mainly attributed to secondary stripping at the front interface of the retained oil layer. During long-term flow, weak interfacial shear causes a small number of tiny oil droplets to detach from the front end of the retained oil layer and be carried away by the water flow. Nevertheless, the main body of the oil layer remains trapped for a long time due to insufficient shear force.

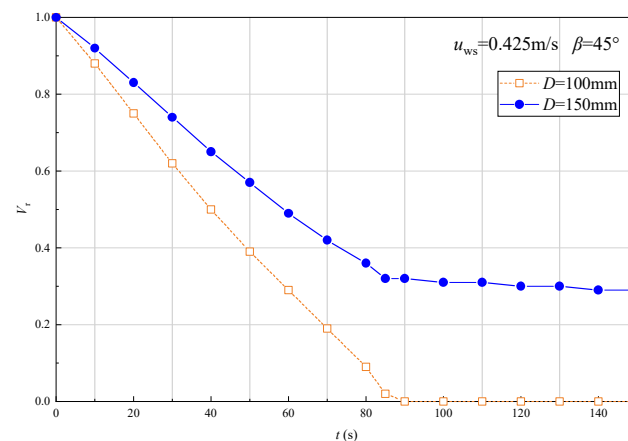


Figure 17. Temporal variation in residual oil volume fraction in the pipe for $D = 100$ mm and $D = 150$ mm.

Therefore, it can be concluded that increasing the pipe diameter significantly raises the threshold of the critical evacuation velocity. Under the condition of $u_{ws} = 0.425$ m/s, the inlet water velocity is sufficient to completely evacuate the 100 mm pipe, but is insufficient to overcome gravitational stratification in the 150 mm pipe, leading to incomplete evacuation.

5. Conclusions

In this paper, oil–water two-phase flow characteristics in an inclined inverted U-shaped mobile pipeline configuration were investigated. A numerical model coupling the VOF interface-capturing method, CSF surface tension model, and SST $k-\omega$ turbulence model was established and validated against experimental data. Based on this validated model, the flow characteristics during water-displacing-oil evacuation in the studied pipeline configuration were systematically analyzed, and the effects of key operating and geometric parameters were clarified. The main conclusions are as follows:

- (1) Driven by the oil–water density difference, no oil accumulation occurs in the upward inclined section of the inclined inverted U-shaped pipe. Given sufficient operating time, the oil phase in this section can be completely displaced by the water phase. The evacuation bottleneck is mainly concentrated in the elbow connected to the upper horizontal section and the downward inclined section.
- (2) A critical inlet superficial water velocity exists under all operating conditions. When the inlet velocity is higher than the critical value, the oil phase can be completely evacuated. When the inlet velocity is lower than the critical value, a retained oil layer forms in the pipe, thereby reducing the evacuation efficiency.
- (3) At the elbow connecting the upper horizontal section and the downward inclined section, loss of lower-wall support at the elbow readily induces the formation of a water slug, resulting in oil accumulation in the upper part of the elbow. The downward inclined section is the main region where retained oil layers occur, which

are formed through the combined effects of the oil-front vortex, internal recirculation, and adverse pressure gradient.

- (4) The pipe inclination angle has a bidirectional regulatory effect on the evacuation performance. When the inlet velocity is subcritical, increasing the inclination angle makes the retained oil layer thicker and reduces the displacement capability. When the inlet velocity is higher than the critical value, increasing the inclination angle accelerates oil-phase migration and shortens the evacuation time.
- (5) Increasing the pipe diameter raises the threshold of the critical evacuation velocity. Under the same inlet velocity, oil retention is more likely to occur in larger-diameter pipes.

It should be noted that the present work is mainly restricted to the No. 0 diesel–water two-phase system at 25 °C, with pipe inclination angle and pipe diameter considered as the primary variables. The study focuses on revealing the oil–water two-phase flow mechanism and summarizing the variation characteristics of the critical evacuation velocity. Therefore, the conclusions obtained herein cannot be fully generalized to mobile pipeline evacuation scenarios involving different oil products, operating temperatures, fluid properties, and broader structural parameters. Future work will extend the range of fluid types, thermophysical properties, temperatures, and pipeline configurations, and will further establish a dimensionless predictive correlation for the critical evacuation velocity with wider applicability, thereby improving the universality and engineering practicality of the present findings.

Author Contributions: Conceptualization, J.D.; Methodology, G.F.; Software, Y.H.; Validation, G.F.; Formal analysis, Y.H.; Investigation, Y.C.; Resources, Y.C.; Data curation, J.L. and J.W.; Writing—original draft, G.F.; Writing—review & editing, J.L.; Visualization, J.L. and J.W.; Supervision, J.D. and Y.C.; Funding acquisition, J.D. and G.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of China (52302422 and 52272338), the Natural Science Foundation of Chongqing, China (CSTB2024NSCQ-MSX1039 and CSTB2024NSCQ-QCXM0080), and a Project of the Science and Technology Research Program of the Chongqing Education Commission of China (KJQN202512909).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Xue, S.; Ouyang, Y.; Lyu, Y. Shutdown–restart flow dynamics and pressure response in inclined oil–water pipelines. *Phys. Fluids* **2026**, *38*, 053115. [\[CrossRef\]](#)
- Abbasov, E.M. Hydrodynamics of the Oil–Water Mixture Flow in a Pipeline. *J. Eng. Thermophys.* **2025**, *34*, 661–670. [\[CrossRef\]](#)
- Li, G.; Fang, G.; Kou, Z.; Chen, S.; Duan, J.; Chen, Y. Oil–Water Hydrodynamics Model during Oil Displacement by Water in Down-Hill Mobile Pipeline. *Processes* **2024**, *12*, 880. [\[CrossRef\]](#)
- Zhao, H.J.; Zhang, D.; Lv, X.F.; Song, L.L.; Li, J.W.; Chen, F.; Xie, X.Q. Numerical Simulation of Crude Oil Leakage from Damaged Submarine-Buried Pipeline. *J. Appl. Fluid Mech.* **2024**, *17*, 75–88. [\[CrossRef\]](#)
- Wu, Y.Y.; Guo, H.M.; Deng, R.; Song, H.W. Effect of flow patterns and velocity field on oil–water two-phase flow rate in horizontal wells. *Geophysics* **2024**, *89*, D61–D74. [\[CrossRef\]](#)
- Yurishchev, A.; Ullmann, A.; Brauner, N. Experiments and modeling of droplets motion induced by turbulent air flow on inclined surfaces. *Exp. Therm. Fluid Sci.* **2023**, *140*, 110763. [\[CrossRef\]](#)
- Yurishchev, A.; Ullmann, A.; Brauner, N. Displacing water from a low spot in a pipeline by a turbulent oil flow: Experiments and simulations. *Chem. Eng. Sci.* **2022**, *262*, 117985. [\[CrossRef\]](#)
- Song, X.; Li, D.; Sun, X.; Mou, X.; Cheng, Y.F.; Yang, Y. Numerical modeling of the critical pipeline inclination for the elimination of the water accumulation on the pipe floor in oil–water fluid flow. *Petroleum* **2021**, *7*, 209–221. [\[CrossRef\]](#)

9. Oladosu, O.; Bhakta, J.; Alba, K. Density-stable yield-stress displacement flow of immiscible fluids in inclined pipes. *J. Non-Newton Fluid* **2020**, *275*, 104203. [[CrossRef](#)]
10. Zhang, D.; Zhang, H.; Rui, J.; Pan, Y.; Liu, X.; Shang, Z. Prediction model for the transition between oil–water two-phase separation and dispersed flows in horizontal and inclined pipes. *J. Petrol. Sci. Eng.* **2020**, *192*, 107161. [[CrossRef](#)]
11. Magnini, M.; Ullmann, A.; Brauner, N.; Thome, J.R. Numerical study of water displacement from the elbow of an inclined oil pipeline. *J. Petrol. Sci. Eng.* **2018**, *166*, 1000–1017. [[CrossRef](#)]
12. Paolinelli, L.D.; Rashedi, A.; Yao, J.; Singer, M. Study of water wetting and water layer thickness in oil–water flow in horizontal pipes with different wettability. *Chem. Eng. Sci.* **2018**, *183*, 200–214. [[CrossRef](#)]
13. Hasnain, A.; Segura, E.; Alba, K. Buoyant displacement flow of immiscible fluids in inclined pipes. *J. Fluid Mech.* **2017**, *824*, 661–687. [[CrossRef](#)]
14. Song, X.; Yang, Y.; Zhang, T.; Xiong, K.; Wang, Z. Studies on water carrying of diesel oil in upward inclined pipes with different inclination angle. *J. Petrol. Sci. Eng.* **2017**, *157*, 780–792. [[CrossRef](#)]
15. Xu, G.; Cai, L.; Ullmann, A.; Brauner, N. Experiments and simulation of water displacement from lower sections of oil pipelines. *J. Petrol. Sci. Eng.* **2016**, *147*, 829–842. [[CrossRef](#)]
16. Pan, Y.X.; Zhang, H.B.; Xie, R.H.; Liu, X.B.; Wang, M. Modeling of low viscosity oil–water annular flow in horizontal and slightly inclined pipes: Experiments and CFD simulations. *Korean J. Chem. Eng.* **2016**, *33*, 2820–2829. [[CrossRef](#)]
17. Hanafizadeh, P.; Hojati, A.; Karimi, A. Experimental investigation of oil–water two phase flow regime in an inclined pipe. *J. Petrol. Sci. Eng.* **2015**, *136*, 12–22. [[CrossRef](#)]
18. Liu, Y.; Wu, N.; Luo, C.; Tian, W.; Li, N.; Cao, G.; Wang, Q.; Gao, C.; Deng, Q. A new criterion for predicting liquid loading in vertical gas wells. *Results Eng.* **2025**, *29*, 108909. [[CrossRef](#)]
19. Hasan, M.Z.; Mondal, D.; Halder, M.R. Numerical analysis of two-phase flow in u-bend pipes: Effects of curvature, and pipe orientation on pressure drop and liquid hold-up. *J. Therm. Eng.* **2026**, *12*, 784–801. [[CrossRef](#)]
20. Jiang, W.; Hai, L.; Yang, X.; Liu, Y. Numerical study of swirl core-annular flow and factors influencing pressure drop in vertical pipelines for oil–water two-phase flow. *Geoenergy Sci. Eng.* **2025**, *244*, 213416. [[CrossRef](#)]
21. Alsanea, M.; Mateus-Rubiano, C.; Karami, H. Experimental study on the effect of liquid properties on fluid behavior and liquid loading in vertical natural gas wells. *Geoenergy Sci. Eng.* **2023**, *230*, 212180. [[CrossRef](#)]
22. Szpunar, T.; Budak, P. The critical flow rates in vertical and horizontal gas/oil wells. *Naft-Gaz* **2022**, 589–597. [[CrossRef](#)]
23. Ganat, T.; Hrairi, M.; Gholami, R.; Abouargub, T.; Motaei, E. Experimental Investigation of Oil–Water Two-Phase Flow in Horizontal, Inclined, and Vertical Large-Diameter Pipes: Determination of Flow Patterns, Holdup, and Pressure Drop. *SPE Prod. Oper.* **2021**, *36*, 946–961. [[CrossRef](#)]
24. Dang, Z.; Yang, Z.; Yang, X.; Ishii, M. Experimental study of vertical and horizontal two-phase pipe flow through double 90 degree elbows. *Int. J. Heat Mass Transf.* **2018**, *120*, 861–869. [[CrossRef](#)]
25. Wang, H.; Xiao, Y.E.; Wang, F.J.; Wang, C.Y.; Liang, Q.W.; Cheng, H.; Xiao, R.F.; Yao, Z.F. Functional mechanism and optimization strategy of dynamic Bradshaw coefficient in SST k-w turbulence model for hydro-energy machinery. *Ocean Eng.* **2026**, *361*, 126152. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.