

Article

RETRACTED: Design and Hydrodynamic Performance Analysis of Airlift Sediment Removal Equipment for Seedling Fish Tanks

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Abstract

This study innovatively proposes a pipeline-type pneumatic lift sediment removal device for cleaning pollutants at the bottom of fish breeding tanks and conducts hydrodynamic characteristic analysis on its core component, the pneumatic lift pipeline structure, which consists of a horizontal circular tube with multiple micro-orifices at the bottom and an upward-inclined circular tube. The pipeline has an inner diameter of 20 mm and a vertical length of 1.2 m, with the orifice at one end of the horizontal tube connected to the gas supply line. During operation, compressed gas enters the horizontal tube, generating negative liquid pressure that draws solid–liquid mixtures from the tank bottom into the pipeline, while buoyant forces propel the gas–liquid–solid mixture upward for discharge through the outlet. Under a constant gas flow rate, numerical simulations investigated efficiency variations through three operational scenarios: ① different pipeline orifice diameters, ② varying orifice quantities and spacings, and ③ adjustable pipeline bottom clearance heights. The results indicate that in scenario ①, an orifice diameter of 4 mm demonstrated optimal efficiency; in scenario ②, the eight-orifice configuration achieved peak efficiency; and scenario ③ showed that the proper adjustment of the bottom clearance height enhances pneumatic efficiency, with maximum efficiency observed at a clearance of 10 mm between sediment suction pipe and tank bottom.

Keywords: gas lift system; three-phase flow characteristics; numerical simulation; lifting efficiency



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1. Introduction

Research Background

During the breeding process of factory-circulated water seedlings, due to the small circulation volume and low flow rate of inlet and outlet water, fecal residues can easily accumulate at the bottom of the tank, causing a large number of microorganisms to breed at the bottom of the breeding tank, which affects the incubation process of fertilized eggs and the healthy growth of seeds. During the nursery period, in order to ensure the cleanliness of the nursery tank, it is necessary to regularly absorb pollutants. Generally, the siphon method is used to remove pollutants at the bottom [1]. This method needs to be completed manually, which can easily lead to fish stress, turbid water, high labor intensity, and uneven

cleaning. In order to solve the problem of the accumulation of residual bait and feces at the bottom of the nursery tank, pipeline-type tank bottom sewage suction equipment based on the pneumatic lifting method was developed, and the pneumatic lifting technology involved in the pipeline-type pneumatic lifting tank bottom sewage suction equipment was studied. This paper explores the gas–liquid–solid three-phase flow characteristics during the pneumatic lift sewage suction process and the influence of the structural form of the pneumatic lift sewage suction equipment at the bottom of the tank on the airlift sewage suction effect.

Due to the outstanding advantages of pneumatic lifting devices, such as their simple structure, high safety, and easy operation, pneumatic lifting systems have been extensively studied and discussed by domestic and foreign researchers since the 1950s and 1960s. Reinemann et al. experimentally studied the lifting efficiency of pneumatic lifting devices with riser diameters between 3 and 25 mm and obtained the changing trend of lifting efficiency [2]. Hewitt et al. observed flow patterns through simultaneous high-speed flash and high-speed X-ray photography and determined the flow patterns of plug flow, agitation flow, annular flow, and thin annular flow [3]. Samaras et al. developed a new flow pattern map based on previous work concerning flow pattern diagrams and corresponding parameters for two-phase flow in pneumatic lifts [4]. To more conveniently describe the performance of pneumatic lift, they directly observed flow pattern transitions and estimated void fractions [4]. Hitoshi et al. investigated the influence of both a straight pipe and an S-shaped pneumatic lifting device with dual risers (positioned below or above the gas ejector) on gas–liquid–solid three-phase flow characteristics [5]. Pougatch et al. used CFD to establish a two-dimensional model based on the multiphase flow Euler method to study the physical characteristics (density, flow velocity, pipeline, etc.) of the flow in the vertical pipeline of the pneumatic lifting device [6]. Hanafizadeh et al. studied the effects of different submersion rates and seven different angles of the tapered riser on the efficiency of the pneumatic lift device based on the two-fluid Euler–Eulerian model and the standard κ – ϵ turbulence model [7,8].

To sum up, most domestic and foreign scholars currently conduct analysis and research on the main working parameters of the pneumatic lifting device, the air intake method, and the flow pattern in the riser. The above works on pneumatic lifting devices primarily use vertical riser tubes, and there are relatively few studies on riser tubes containing local bends. Therefore, the research focus of this article is on the pneumatic lifting technology involved in pipeline-type (including partial bends) pneumatic lifting devices, exploring the gas–liquid–solid three-phase flow characteristics during the pneumatic lifting sewage suction process, and the effect of the structural form of pneumatic lifting pool bottom sewage suction equipment on the airlift sewage suction effect.

2. Materials and Methods

2.1. Pneumatic Lifting Sewage Suction Device System Composition

The pneumatic sediment lifting system primarily consists of a suction pipe, elevating pipelines, a concentrated tank, a rotation axis, and a gear motor. As shown in Figure 1, during operation, an air pump injects gas into the air inlet of the suction pipe. Since the bottom surface of the suction pipe features multiple perforations, high-velocity air flow from the suction pipe outlet to the upper port of the lifting pipe creates lower pressure inside the suction pipe than in the area beneath the perforations due to the Bernoulli effect. This pressure differential draws water–solid mixtures into the suction pipe, where continuous air flow propulsion transports the mixture upward through the lifting pipe. Waste materials are ultimately collected in the tank, with accumulated wastewater being manually drained at regular intervals. Between the lifting pipe and collection tank, a

rotational connection is achieved via a rotating shaft and bearing block. The configuration of a gear motor with reduction gears enables the lifting pipe and suction pipe to rotate around the central axis of the fish tank, thus facilitating comprehensive sediment removal across the entire tank bottom. This airlift sediment removal system features high cleaning efficiency, minimal disturbance to fish, and low maintenance costs.

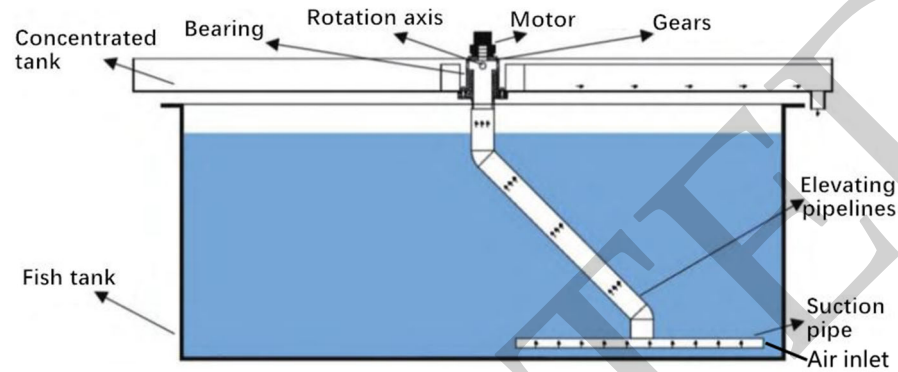


Figure 1. System composition of the airlift and sewage suction device.

Figure 2 is a physical diagram of the pneumatic lifting sewage suction test device. The control system of the sea cucumber dual-channel sewage discharge device is mainly composed of a touchscreen PLC-integrated machine, a DC motor drive board, and a switching power supply. Then, the instruction is sent to the PLC through the touchscreen. After receiving the instruction, the PLC controls the starting and stopping of the DC motor according to the requirements and adjusts the speed of the DC motor through the DC motor driver board. After the airlift rotary sewage discharge device is started, the residual bait and feces at the bottom of the breeding tank will be sucked into the sewage trough with the airlift pipe and flow through the disc-shaped particulate sewage discharge device to the high-efficiency treatment device for aquaculture tailwater.



Figure 2. Physical picture of the test device.

2.2. Theoretical Analysis Foundation

2.2.1. Continuity Equation

The continuity equation for fluids adheres to the law of mass conservation. Formulated for a fluid control volume, its expression is as follows [9]:

$$\frac{\partial \rho}{\partial t} + \left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} \right] = 0 \quad (1)$$

Introducing vector notation:

$$\text{div}(a) = \frac{\partial a_x}{\partial x} + \frac{\partial a_y}{\partial y} + \frac{\partial a_z}{\partial z} \quad (2)$$

Equation (1) can be transformed to:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho u) = 0 \quad (3)$$

In Equations (1)–(3), ρ denotes the fluid density; t represents time; u , v , and w are velocity components in the x , y , and z directions, respectively; and a_x , a_y , and a_z signify acceleration components along the x , y , and z axes.

2.2.2. Momentum Equations

Within flow fields, the governing equations derived from Newton's Second Law constitute the momentum equations. The resultant force acting on a fluid element numerically equals the rate of momentum change entering the element per unit time, thus establishing the momentum conservation equations [10]:

$$\frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u u) = -\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x \quad (4)$$

$$\frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v u) = -\frac{\partial P}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + F_y \quad (5)$$

$$\frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w u) = -\frac{\partial P}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + F_z \quad (6)$$

In Equations (4)–(6), P denotes the pressure applied to the fluid element; $\text{div}(\rho u u)$, $\text{div}(\rho v u)$, and $\text{div}(\rho w u)$ represent the divergence of $\rho u u$, $\rho v u$, and $\rho w u$, respectively; τ signifies viscous stress; τ_{xx} , τ_{xy} , τ_{xz} , τ_{yz} , τ_{zx} , τ_{yy} , τ_{yz} , τ_{zy} , and τ_{zz} are components of the spatial viscous stress tensor arising from viscous effects; and F_x , F_y , and F_z indicate force components acting on the fluid element along the x , y , and z axes. For Newtonian fluids, the following relationship holds [11]:

$$\begin{cases} \tau_{xx} = 2u \frac{\partial u}{\partial x} + \lambda \text{div}(u) \\ \tau_{xy} = \tau_{yx} = u \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \end{cases} \quad (7)$$

$$\begin{cases} \tau_{xx} = 2u \frac{\partial u}{\partial x} + \lambda \text{div}(u) \\ \tau_{xy} = \tau_{yx} = u \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \end{cases} \quad (8)$$

$$\begin{cases} \tau_{xx} = 2u \frac{\partial u}{\partial x} + \lambda \text{div}(u) \\ \tau_{xy} = \tau_{yx} = u \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \end{cases} \quad (9)$$

In Equations (7)–(9), λ denotes the second viscosity coefficient (typically valued at -2 to 3); and u represents dynamic viscosity.

Substituting Equations (7)–(9) into Equations (4)–(6) yields:

$$\begin{cases} \frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u u) = \text{div}[\mu \text{grad}(u)] - \frac{\partial p}{\partial x} + S_u \\ \text{grad}() = \partial()/\partial x + \partial()/\partial y + \partial()/\partial z \end{cases} \quad (10)$$

$$\frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v u) = \text{div}[\mu \text{grad}(v)] - \frac{\partial p}{\partial y} + S_v \quad (11)$$

$$\frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w u) = \text{div}[\mu \text{grad}(w)] - \frac{\partial p}{\partial z} + S_w \quad (12)$$

In Equations (10)–(12), S_u , S_v , and S_w denote generalized source terms for the momentum equations, where $S_u = F_x + S_x$, $S_v = F_y + S_y$, $S_w = F_z + S_z$. For viscous incompressible fluids, S_x , S_y , and S_z are identically zero.

2.2.3. Parameter Design Theory

The design parameters of pneumatic lifting systems primarily include the diameter of the lifting pipe, the gas inlet flow rate, and the submergence ratio of the pipe when underwater. Gas–liquid flow patterns in pneumatic lifting pipes are categorized into four types according to flow pattern maps: annular flow, slug flow, bubble flow, and churn flow. The diameter of the lifting pipe is typically calculated based on the governing equations for slug flow conditions [12–14]:

$$D = \frac{\mu_g^2 \gamma_2}{\mu_g^{*2} g \gamma_1} \quad (13)$$

$$\mu_g = \frac{Q_g}{h} \quad (14)$$

$$\mu_g^* = 0.0061 + 0.007 \mu_1^* \quad (15)$$

$$\mu_1^* = \frac{\mu_1}{\sqrt{g \delta}} \quad (16)$$

$$\mu_1 = \frac{Q}{h} \quad (17)$$

$$h = \frac{H}{\varphi - 1} \quad (18)$$

$$Q_g = \frac{KQH}{\left(231g^{\frac{h+10}{h}}\right)\delta} \quad (19)$$

In this formula, D is the diameter of the pneumatic lifting pipeline, m; μ_g is the superficial velocity of the gas phase, m/s; μ_g^* is the modified Froude number for the gas phase; g is the acceleration due to gravity, m/s²; γ_1 is the volumetric weight of the liquid phase, kg/m³; γ_2 is the volumetric weight of the gas phase, kg/m³; Q_g is the gas flow rate, L/min; δ is the efficiency coefficient, typically ranging from 0.35 to 0.45; h is the submerged height of the riser pipe, m; H is the lifting height of the riser pipe, m; φ is the density coefficient, with a value range of 2 to 2.5; Q is the theoretical design flow rate for lifting in the airlift conduit, m³/h; and K is the safety factor, 1.2.

The pneumatic lifting efficiency is a primary performance metric for evaluating the operational performance of gas–liquid–solid lifting systems, and its calculation formula can be expressed as follows:

$$\eta = \frac{\rho_g Q_L (L - H_S)}{P_a Q_G \ln(P_m / P_a)} \quad (20)$$

In this formula, L is the total distance between the pipeline's inlet and outlet, m; H_S is the pipeline's immersion depth, m; Q_L is the solid–liquid two-phase volume flow rate, m³/s; Q_G is the gas phase volume flow rate, m³/s; P_m is the inlet pressure, Pa; and P_a is the standard pressure, Pa.

2.3. Technical Research Routes

Given the complex internal flow characteristics and low efficiency of pneumatic lifting systems, numerical simulation methods were employed to study their multiphase flow

behavior [15,16]. This analysis examines gas–liquid–solid three-phase flow characteristics under specific operating conditions and evaluates the impact of the gas injection configuration on lifting velocity and efficiency. The technical approach is illustrated in Figure 3.

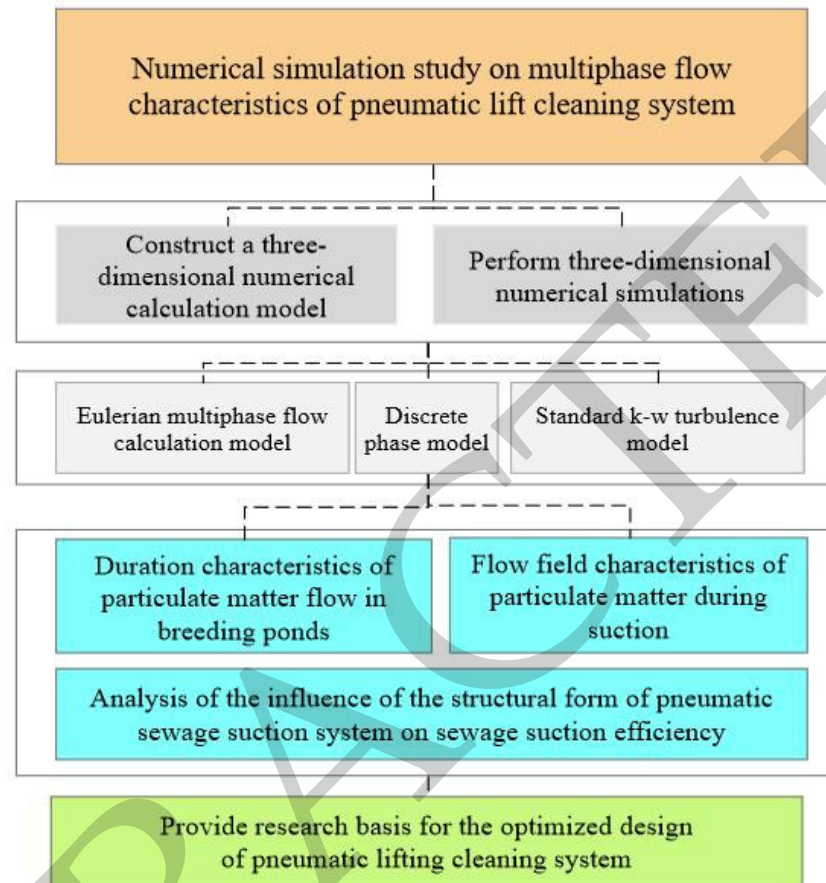


Figure 3. Technology roadmap.

2.4. Numerical Simulation Analysis

This study employs ANSYS Fluent 2024 R2 for computational fluid dynamics simulations. Primary pollutants in aquaculture tanks originate from fish excrement, residual feed, and fine particulate matter. To investigate particle deposition patterns and distribution dynamics within the tank—providing a foundation for optimizing sediment removal systems—a discrete phase model (DPM) was implemented to simulate particulate pollutant settling. The recirculating aquaculture tank (Figure 4) features a 2 m diameter, 1.3 m height, 1 m water depth, 28 mm inlet diameter, 50 mm bottom outlet diameter, and 6 h daily circulation cycle. Figure 5 displays the meshed computational domain for particle flow regime analysis, comprising $\approx 260,000$ volume elements with 15 mm base sizing. Local refinement to 2 mm was applied at the inlet region.

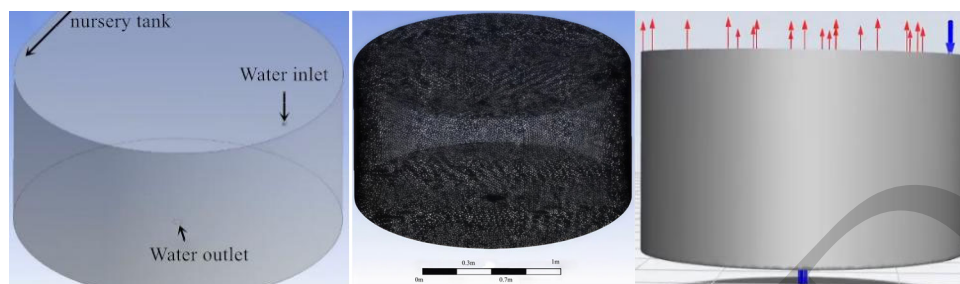


Figure 4. Particle deposition model diagram and boundary condition settings.

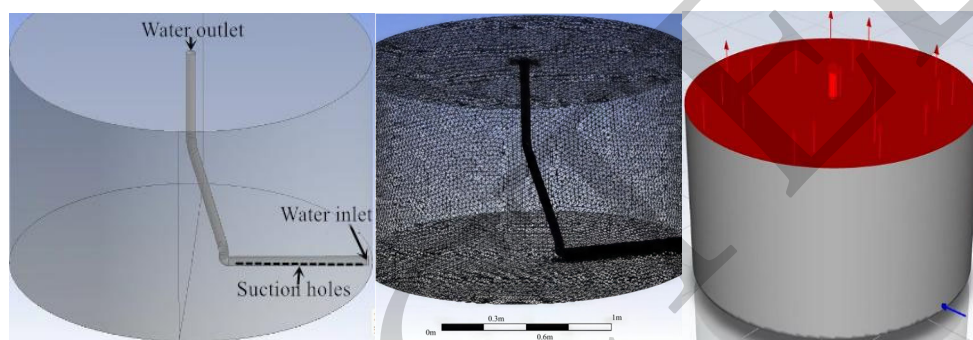


Figure 5. Pneumatic lifting system model and boundary condition settings.

Figure 4 delineates the boundary conditions for the particulate pollutant flow model within the fish breeding tank, employing the pressure-based phase-coupled SIMPLE algorithm [17] with initial configurations comprising a 1.0 m water depth, mass flow inlet at the water intake, mass flow outlet at the bottom drain, pressure outlet (101.325 kPa) at the water surface, and a water particulate multiphase system featuring spherical particles (diameter: 0.1 mm, density: 1050 kg/m³) in water (density: 998 kg/m³). High-resolution discretization schemes ensured accuracy via the QUICK scheme for turbulence intensity, a second-order implicit formulation for transient terms, and default settings for the remaining parameters.

The structural configuration of the pneumatic lift pipeline and its immersion depth constitute the primary determinants of the sewage suction system's performance. The pneumatic lift device model comprises a simplified riser structure immersed in the fish tank, where compressed air injection through the supply pipe initiates complex gas–liquid–solid three-phase flow regimes within the riser. Given that the breeding tank diameter substantially exceeds that of the riser tube and exhibits a negligible impact on lift performance, computational simulations require only the constant maintenance of the tank's water level.

Figure 5 presents the structural model of the pneumatic lift sediment removal device's gas–liquid–solid three-phase flow system. The riser features a total length (L) of 1.98 m, with 1.68 m submerged (immersion ratio: 0.85). Multiple water inlets and a single air inlet with a 10 mm diameter are positioned at the riser's base.

To determine appropriate mesh dimensions, grid independence verification was conducted by employing three mesh sizes (0.01 m, 0.03 m, and 0.05 m) for discretization; the meshed models were subsequently imported into the Fluent solver for numerical simulation, with computational results compared across these configurations. The average computational error of the 0.01 m mesh relative to the 0.03 m mesh measured 4.18%, while the 0.05 m mesh exhibited a 2.64% error relative to the 0.03 m benchmark. Considering computational accuracy and time efficiency, the primary mesh size was set to 0.03 m with local refinement to 0.01 m in critical regions, yielding a final mesh comprising 47,500 elements.

Computational analysis employed the Eulerian multiphase model coupled with the discrete phase model and standard k - ω turbulence model. Initial conditions included a 1 m

water level, an air-phase velocity inlet boundary, pressure outlets (standard atmospheric pressure) at the bottom outlet and water surface, and uniformly distributed sediment particles forming a 12 mm accumulation layer at the tank's bottom. The remaining parameters retained their default settings.

3. Results

3.1. Particulate Pollutant Flow Pattern Analysis

The numerical analysis of particulate pollutant deposition processes [14] reveals distinct transport phases, as depicted in Figure 6. The simulation initialized particles uniformly distributed at the aquaculture tank's free surface, with iterative computation capturing their temporal evolution under hydrodynamic circulation patterns. Figure 6 demonstrates four sequential transport regimes:

- (1) Suspension stage: Particulate matter enters the water from the upper surface and initially appears suspended in the upper layer of the water, as shown in Figure 6a.
- (2) Descending stage: Under the influence of the water in and out of the fish tank, the particles in the upper layer of the water surface near the water inlet are impacted by the vertical water inflow to the lower layer of the water surface, as shown in Figure 6b.
- (3) Sedimentation stage: The falling particulate matter gradually diffuses to the entire water area through reflection from the fish tank wall, resulting in disordered flow, as shown in Figure 6c.
- (4) Stable stage: When the water circulation of the fish tank reaches a stable state, the distribution of particles gradually reaches a stable state. The upper layer of the water area is in a suspended state, the lower layer of the water area is in a sedimentary state, and the middle layer of the water area is in a turbulent state under the action of water circulation, as shown in Figure 6d.

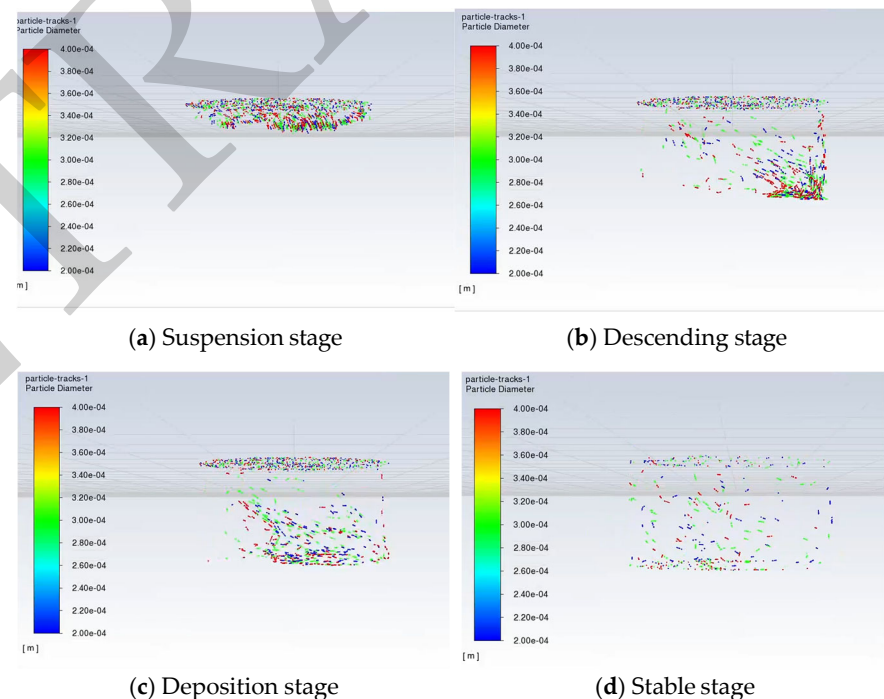


Figure 6. Particulate matter flow duration stages.

Statistics on the quantity distribution of particulate matter when it reaches a stable state in the fish tank can be obtained: sedimentary particulate matter accounts for approx-

imately 26.7% of the total particulate matter, suspended particulate matter accounts for approximately 14.5%, and turbulent particulate matter accounts for approximately 58.8%.

3.2. Gas–Liquid–Solid Three-Phase Flow Analysis During Sewage Suction

Building upon the numerical analysis of particulate pollutant deposition in preceding sections, this study investigates pneumatic lift suction dynamics and particulate transport characteristics within the riser pipeline. Simulations were implemented in the Fluent solver through discrete phase volume initialization, featuring zoned initialization of stratified regions to replicate uniformly distributed sedimentation particles at the bottom of the aquaculture tank. Leveraging the Eulerian multiphase model and previously established boundary conditions, the computational analysis reveals multiphase flow patterns, as detailed in Figures 7 and 8. The figures use density cloud diagrams and volume fraction cloud diagrams to show the gas–liquid–solid three-phase flow during the pneumatic lifting sewage suction process. The flow process can be divided into the following four stages:

- (1) Initial stage: The sedimented particles are evenly distributed at the bottom of the breeding fish tank. The average height of the particle area is 12 mm, the density of the particle area is 1485 kg/m^3 , the density of water is set to 1000 kg/m^3 , and the density of air is set to 1.29 kg/m^3 . The initial stage shows the density and volume fraction cloud diagrams of the gas, liquid, and solid phases in the water when the air inlet is not opened, as shown in Figures 7a and 8a.
- (2) Pressure relief stage: Within a period of time after the air inlet is opened, air enters the inside of the gas lift pipe through the jet opening. Since the liquid level inside the pipeline is flush with the water surface before the air inlet is opened, under the action of the water pressure inside the pipeline, the jetted air flow is blocked and turns to the water inlet at the lower end of the airlift pipeline for pressure relief. This causes the particles at the bottom to be locally diffused by the pressure relief force, and at the same time, gas escape and bubble diffusion are produced, see Figures 7b and 8b.
- (3) Lifting stage: After the pressure relief stage, the original water flow in the pipeline is lifted to the outside of the fish tank by the incident air flow. At this time, the air phase is the main phase in the pipeline, and the flow rate increases. Under the action of the Bernoulli effect (the greater the flow rate, the lower the pressure), the particles flow into the pipeline from the water inlet and are lifted upward under the action of the air flow, see Figures 7c and 8c.
- (4) Stable stage: When the gas phase pressure in the pneumatic lifting pipeline reaches stability, the two-phase liquid–solid mixed with water and particulate matter continuously flows into the pipeline from the water inlet, and the three-phase gas–liquid–solid flow continues from the bottom of the pipeline to the upper outlet, as shown in Figures 7d and 8d.

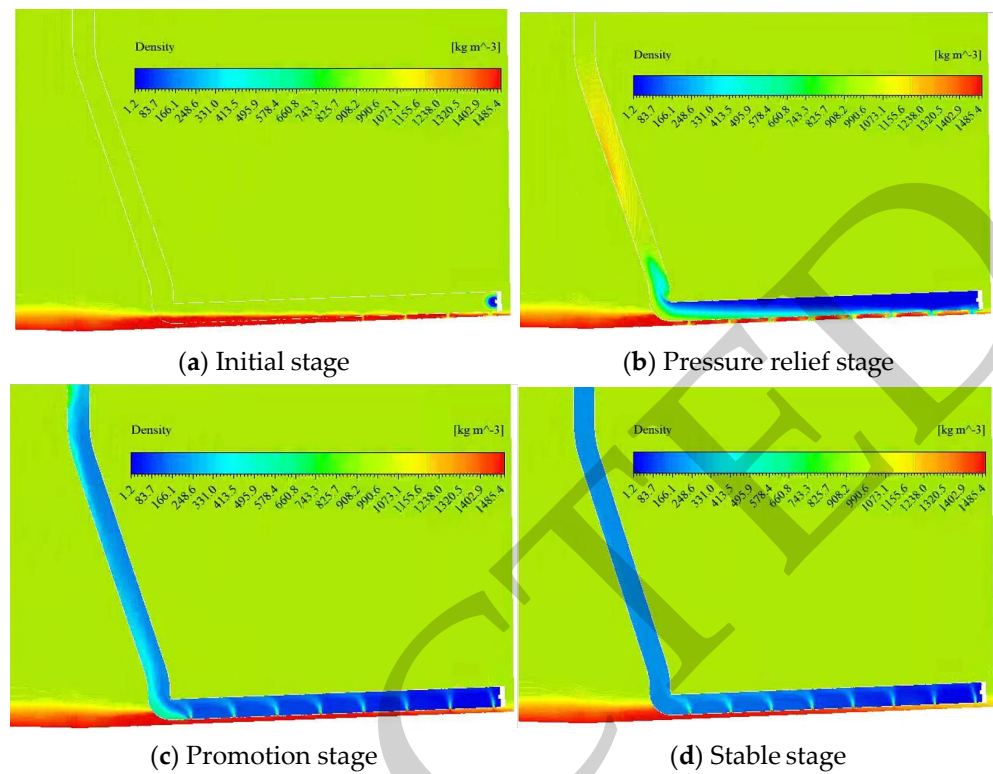


Figure 7. Pneumatic lifting stage of particulate pollutants.

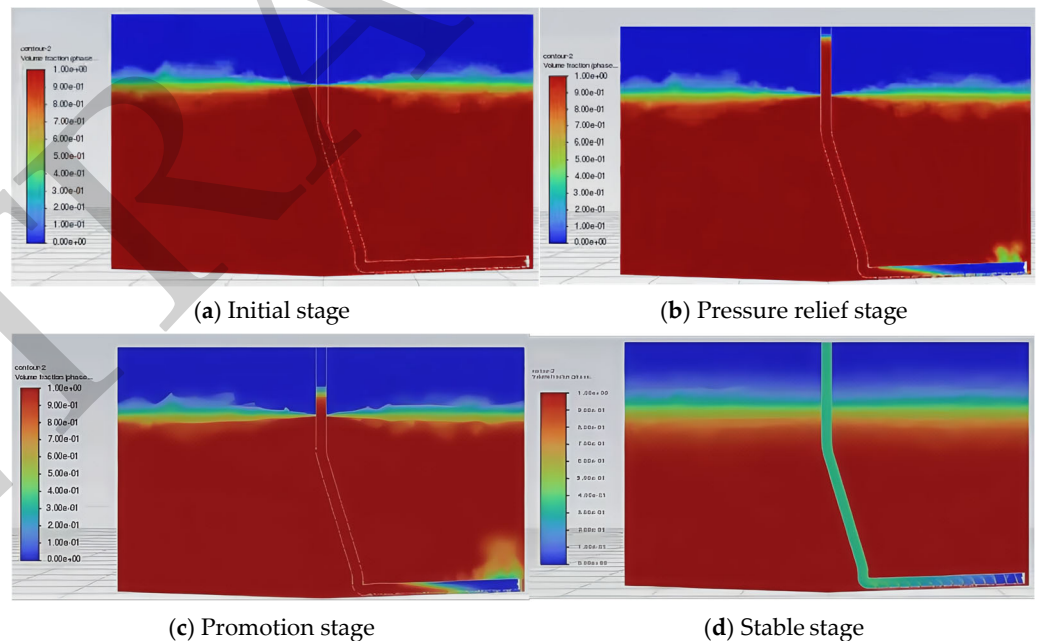


Figure 8. Volume fraction contour plot for the pneumatic sediment removal process.

The statistics of the flow velocity distribution of particulate matter when the gas–liquid–solid three-phase flow in the gas-stripping pipeline reaches a stable state and can be obtained; the outlet flow rate of the gas-stripping pipeline in the stable stage is about 0.85 m/s, and the mass flow rate of particles is about 0.72 m³/h.

3.3. The Impact of the Structural Layout of the Sewage Suction Device on Sewage Suction

The structural configuration and submersion depth of pneumatic lift pipes significantly influence sediment removal efficiency. Figures 9 and 10, respectively, display the vorticity contours and velocity vector distributions within the operating airlift system.

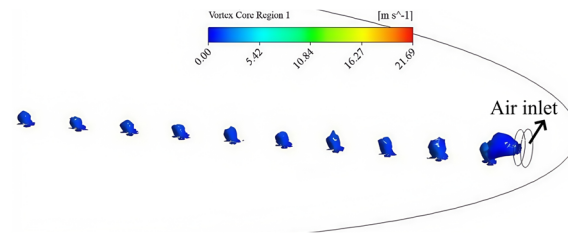


Figure 9. Flow velocity vorticity distribution diagram in the pneumatic lift pipeline.

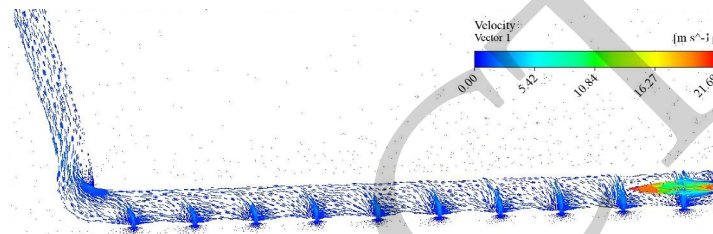


Figure 10. Vector diagram of flow velocity in the pneumatic lift pipeline.

Figure 9 reveals a velocity gradient along the suction pipe's inlet ports: flow rates proximal to the gas injection point exceed those at distal ports. Figure 10's velocity vector plot quantifies this phenomenon, with post-processing data indicating a 21.69 m/s gas-phase velocity at the injection point. Adjacent inlet ports exhibit an average velocity of ~5 m/s, decreasing to ~3.8 m/s at the furthest port, confirming progressive velocity attenuation along the pipe axis.

This flow distribution analysis demonstrates that injector port design and placement critically determine pneumatic sediment removal efficacy. Consequently, we investigate three key parameters governing suction performance: the inlet port diameter, number of ports, and pipe submergence ratio.

3.3.1. Opening Diameter

While maintaining constant gas inlet flow, numerical simulations were performed for three airlift configurations with distinct port diameters (2 mm, 3 mm, and 4 mm). The results are presented in Figures 11–13.

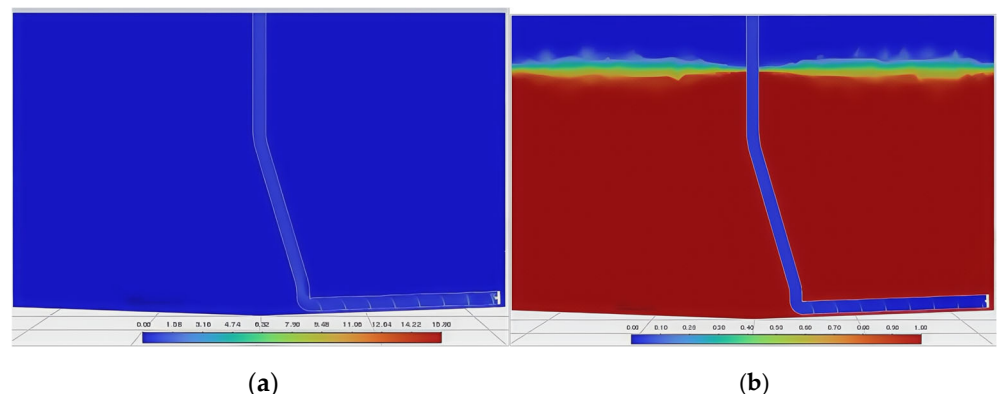


Figure 11. (a) Velocity distribution with a 2 mm opening. (b) Volume fraction of a 2 mm opening.

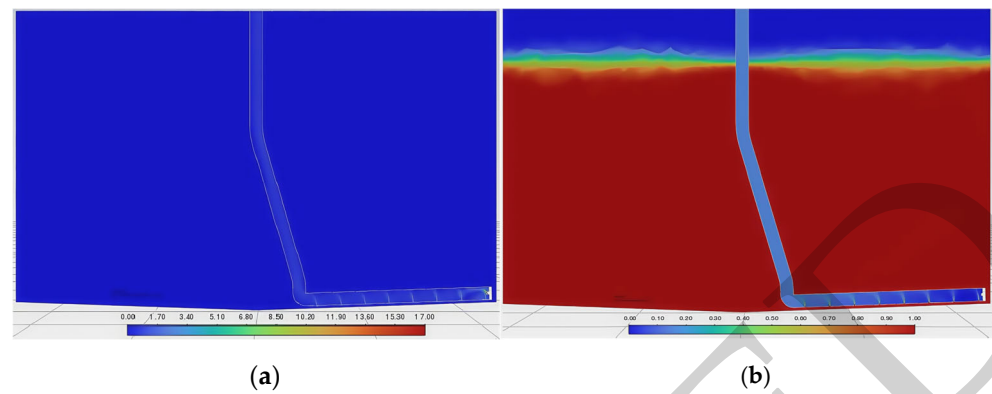


Figure 12. (a) Velocity distribution of a 4 mm opening. (b) Volume fraction of a 4 mm opening.

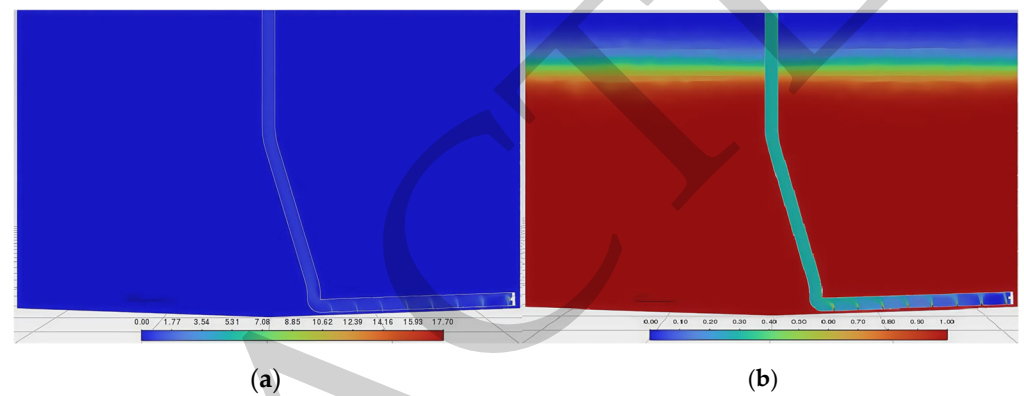


Figure 13. (a) Velocity distribution of a 6 mm opening. (b) Volume fraction of a 6 mm opening.

Subfigure (a) demonstrates the steady-state velocity distributions at each diameter. These reveal progressively higher gas–liquid–solid phase velocities with increasing port sizes. Subfigure (b) displays the corresponding volume fraction distributions, showing enhanced transport efficiency: larger ports yield greater gas–solid–liquid phase concentrations at the outlet, indicating higher particulate sewage intake capacities.

Statistics were produced on the time-dependent flow rates of the gas, liquid, and solid phases at the outlet position, and the average flow rate time-lapse curves at the pipeline outlet under different opening diameters were drawn, as shown in Figure 14. In Figure 14, the abscissa is the time duration from the initial stage to the stable stage of the pneumatic lifting pipeline, the unit is seconds (s), and the ordinate is the flow rate of the gas–liquid–solid three-phase outlet, where the unit is meters/second (m/s).

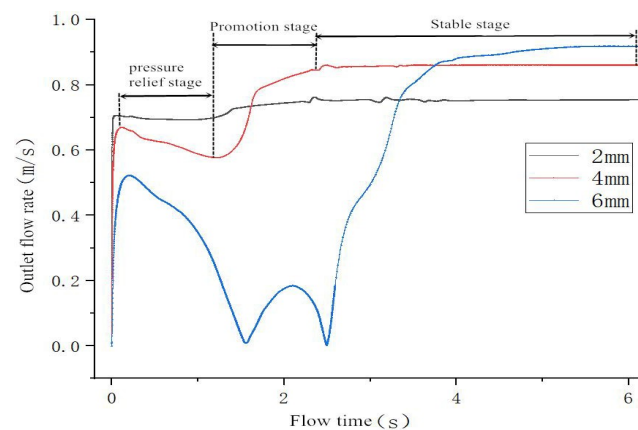


Figure 14. Efficiency curves of the pneumatic lift system at varying orifice sizes.

It can be seen from Figure 15 that the flow rate change curve of the gas, liquid, and solid phases at the outlet position basically conforms to the above four stages, including the initial stage, when the air intake has not started, the pressure relief stage, the effect of the gas phase on the initial pressure escape, the lifting stage, where the pressure in the pipeline gradually becomes stable and air occupies the main phase, and the stable stage, where the flow rate of the gas, liquid, and solid phases is stable.

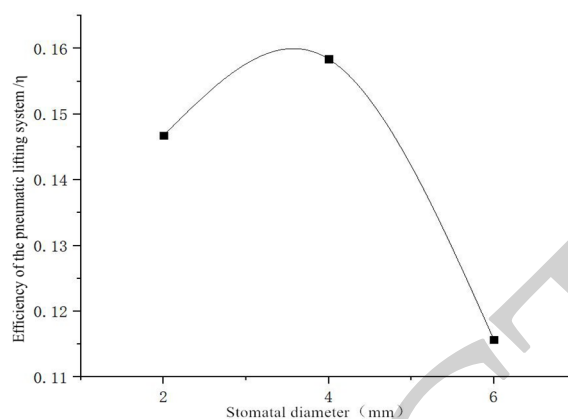


Figure 15. Average flow velocity duration curve.

At the same time, when comparing the outlet flow velocity distribution under three different opening diameters (2 mm, 4 mm, and 6 mm), it can be seen that when the air inlet flow rate remains unchanged, the larger the opening diameter, the higher the flow rate after the gas–liquid–solid three-phase reaches a stable stage. However, at the same time, the larger the diameter of the opening, the longer it takes for the gas, liquid, and solid phases to reach a stable stage, that is, the duration of the pressure relief stage and the lifting stage increases, and the air flow disturbance caused by the bottom particles becomes more obvious. This will directly affect the original bottom particle deposition and adversely affect the sewage suction effect.

The pneumatic lifting efficiency formula of the pneumatic lifting system is used to calculate and solve the pneumatic lifting efficiency η of the pipeline under three different opening diameters. The outlet flow rate QL is obtained by integrating the outlet flow rate curve in Figure 14. At the same time, the pressure P_m at the air inlet can be obtained based on the pressure calculation results in the post-processing results. The remaining parameters are all known. After data processing, the efficiency curve of the pneumatic lift system is obtained, as shown in Figure 14 below. It can be seen from the figure that when the air inlet flow rate remains unchanged, the efficiency of the pneumatic lift system first increases and then decreases as the opening diameter increases. The efficiency of the pneumatic lifting system is the highest when the opening diameter is 4 mm, with a value of about 0.16.

3.3.2. Number of Holes

The following analyzes the influence of the number of openings and the spacing between openings on the sewage suction performance of pneumatic lifting pipelines when the air inlet flow rate and opening diameter remain unchanged. Three gas-stripping pipelines with different opening numbers and opening spacings were selected for numerical calculation. The numerical analysis results are shown in Figures 16–19 below. Figures 16a, 17a, 18a and 19a, respectively, show the flow velocity distribution inside the pipeline after reaching a stable stage, with eight openings, eight variable-pitch openings, fourteen openings, and twenty openings.

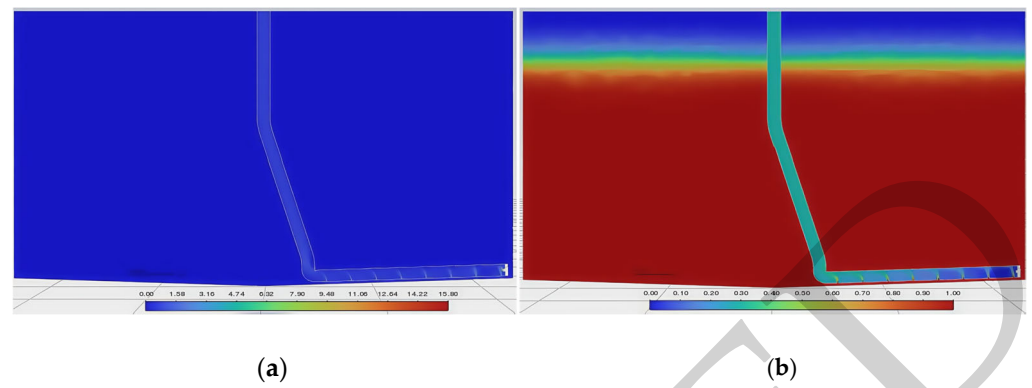


Figure 16. (a) Velocity distribution of 8 holes. (b) Volume fraction of 8 holes.

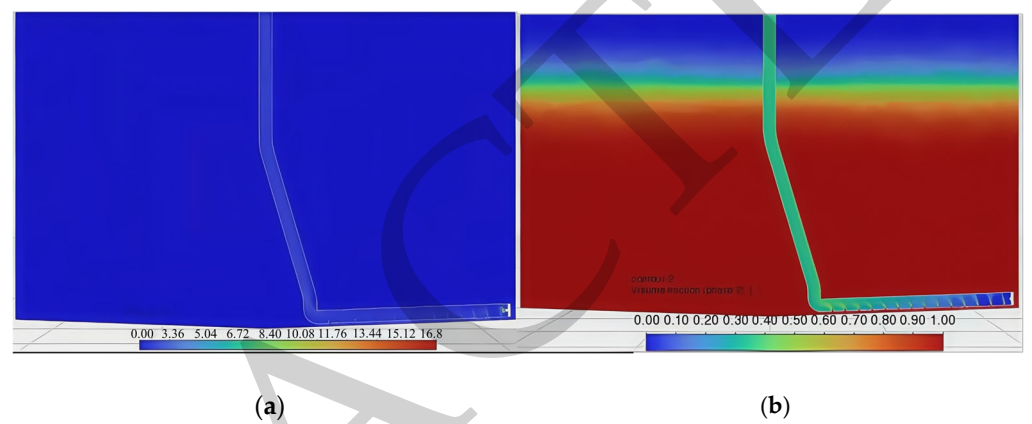


Figure 17. (a) Velocity distribution of 8 variable-pitch holes. (b) Volume fraction of 8 variable-pitch holes.

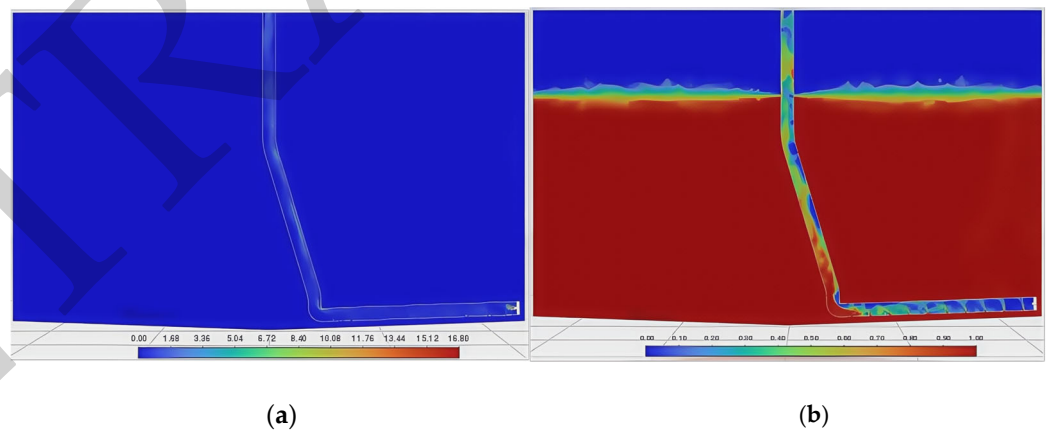


Figure 18. (a) Velocity distribution of 14 holes. (b) Volume fraction of 14 holes.

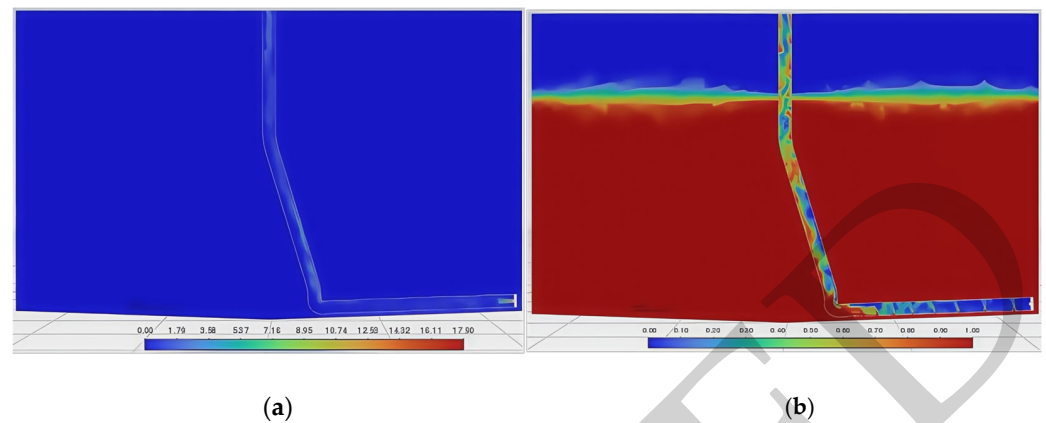


Figure 19. (a). Velocity distribution of 20 holes. (b). Volume fraction of 20 holes.

It can be seen that as the number of openings increases, the flow rate uniformity of the gas, liquid, and solid phases gradually decreases after reaching a stable stage. Figures 16b, 17b, 18b and 19b, respectively, show the internal stability of the pipeline with eight openings, eight variable-pitch openings, fourteen openings, and twenty openings. From the volume fraction distribution after this stage, it can be seen that as the number of openings increases, the uniformity of the volume fraction of the gas–liquid–solid three-phase flow inside the pipeline from the air flow to the outlet also decreases. At the same time, with the same number of openings, changing the spacing will not have a major impact on the flow field velocity distribution and volume fraction distribution.

It can be seen that an increase in the opening area will cause a loss of internal pressure in the pneumatic lift pipeline, resulting in the disorder of the gas–liquid–solid three-phase flow pattern and causing solid–liquid two-phase accumulation at the bottom of the pipeline, which affects the pneumatic lift’s sewage suction effect. When changing the hole spacing with the same number of openings, the flow velocity distribution and volume fraction distribution inside the pipeline will not be disordered. The volume fraction of the solid–liquid two-phase flow inside the pipeline is higher, which means that under the steady state of the three-phase flow, the solid–liquid two-phase outflow rate is higher after changing the pore distance.

The flow velocity of the gas, liquid, and solid phases at the outlet position was statistically analyzed over time, and the average flow velocity at the pipeline outlet with different numbers of openings over time was drawn, as shown in Figure 20.

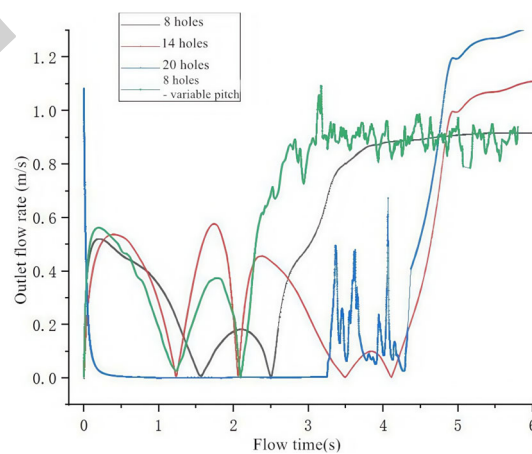


Figure 20. Average flow velocity duration curve of the pipeline outlet under different openings.

Comparing the outlet flow velocity distribution of three different opening numbers (eight holes, fourteen holes, and twenty holes) and the variable pitch of eight openings, it can be seen that when the air inlet flow rate and hole diameter remain unchanged, the greater the number of openings, the higher the flow rate after the gas–liquid–solid three-phase flow reaches the stable stage. However, at the same time, the increase in the number of openings increases the time taken for the gas–liquid–solid three-phase flow to reach the stable stage, that is, the duration of the pressure relief stage and the lifting stage increases. This will directly affect the original bottom particle deposition and adversely affect the sewage suction effect. At the same time, it can be seen from the above that an increase in the number of openings (an increase in the open cross-sectional area) will cause a certain degree of disorder in the three-phase flow, affecting the efficiency of the pneumatic lift sewage suction system. While the number of openings remains unchanged, changing the distance between each adjacent water inlet can increase the speed at which the gas, liquid, and solid phases reach the stable stage to a certain extent. At the same time, after reaching the stable stage, the outlet flow rate will oscillate slightly. The amplitude is ± 0.1 m/s. For a detailed analysis, see Figure 21 below.

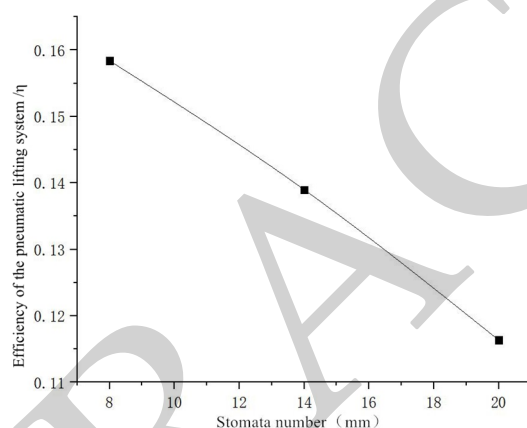


Figure 21. Efficiency curve of the pneumatic lifting system under different openings.

The pneumatic lifting system lifting efficiency formula can be used to calculate and solve the pneumatic lifting efficiency η of the pipeline under three different opening diameters and obtain the pneumatic lifting system efficiency curve, as shown in Figure 23 below. It can be seen from the figure that when the air inlet flow rate and hole diameter remain unchanged, the efficiency of the pneumatic lifting system shows a decreasing trend when the number of openings increases. The efficiency of the pneumatic lifting system is the highest when the number of openings is eight, at about 0.158. When the number of openings is 20, the efficiency is greatly reduced to about 0.115. It can be seen that for this pneumatic lifting pipeline system, we should try to avoid opening too many water inlet holes; otherwise, it will cause air leakage inside the pipeline and liquid–solid three-phase imbalance. When the spacing of the openings is changed, the efficiency of the pneumatic lift piping system is calculated to be 0.164. It can be seen that when the number of openings remains unchanged, appropriately adjusting the openings' spacing will be beneficial to the efficiency of the pneumatic lift sewage suction system.

3.3.3. Height of the Sewage Suction Pipe from the Bottom

To evaluate the impact of submergence height (distance from the tank's bottom) on pneumatic sediment removal efficiency under constant gas flow, port diameters, and port quantities, three airlift configurations with distinct submergence heights (10 mm, 20 mm, and 30 mm) were numerically analyzed. Figures 22–24 present the results, where subfigures

(a) demonstrate progressive velocity uniformity degradation in gas–liquid–solid phases with increasing height during steady operation. The corresponding subfigures (b) reveal analogous reductions in the volume fraction uniformity of air-lifted multiphase flows at the outlet. Elevated submergence decreases pressure differentials within the conduit, reducing the gas injection pressure that disrupts multiphase flow patterns and promotes solid–liquid accumulation at the pipe base, ultimately compromising suction efficacy.

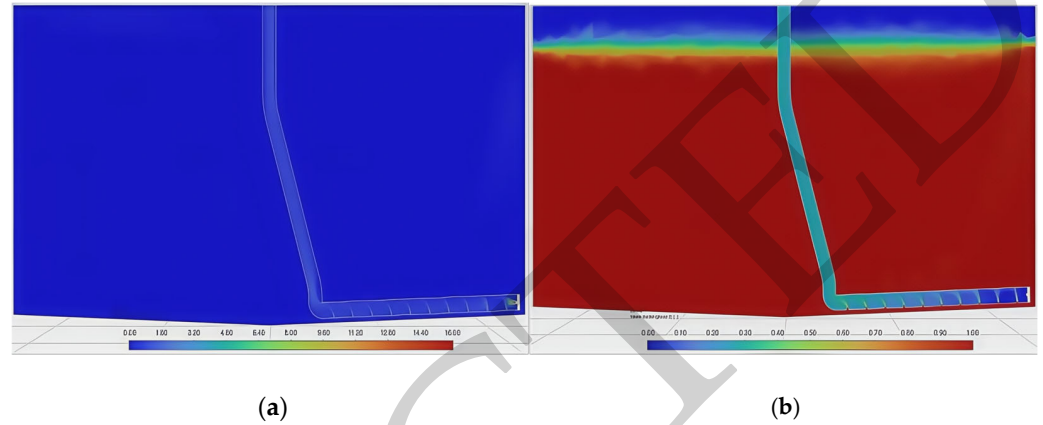


Figure 22. (a). Velocity distribution at 10 mm from the bottom. (b). Volume fraction at 10 mm from the bottom.

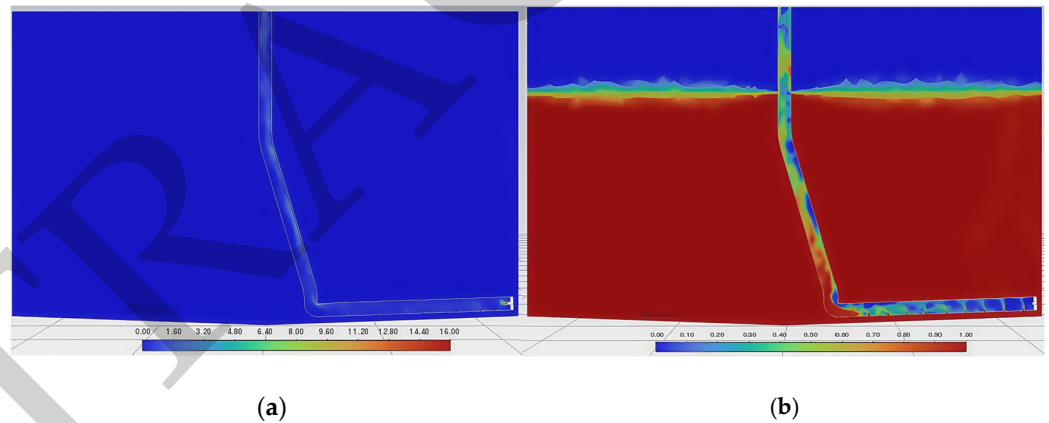


Figure 23. (a). Velocity distribution at 20 mm from the bottom. (b). Volume fraction at 20 mm from the bottom.

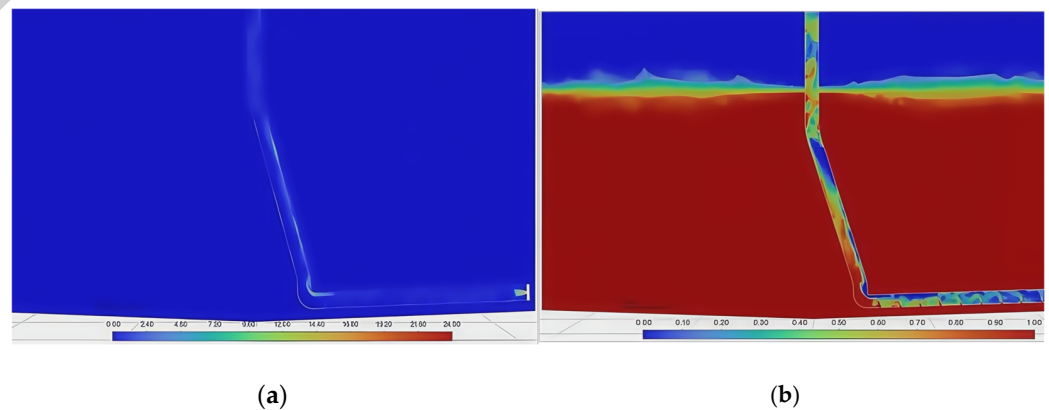


Figure 24. (a). Velocity distribution at 30 mm from the bottom. (b). Volume fraction at 30 mm from the bottom.

The flow rates of the gas, liquid, and solid phases at the outlet position were statistically analyzed over time, and the curve of the average flow rate over time of the pipeline outlet at the height from the bottom was drawn, as shown in Figure 25. Comparing the outlet flow velocity distribution of three different heights from the bottom (10 mm, 20 mm, and 30 mm), it can be seen that when the air inlet flow rate, hole diameter, and number of openings remain unchanged, the outlet flow rate will decrease as the height from the bottom increases, and the increase in the height from the bottom will lead to an increase in the turbulence of the three-phase flow. An excessive height from the bottom will make it difficult for the pneumatic lift system to reach the stable flow stage of the three-phase flow, which will greatly affect the efficiency of the pneumatic lift sewage suction system.

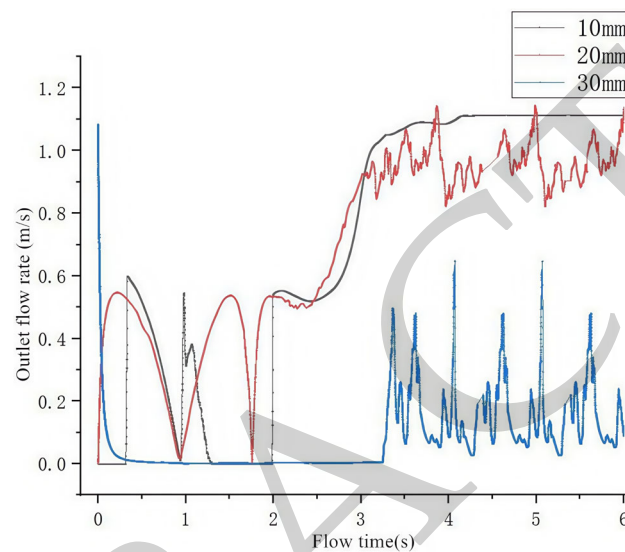


Figure 25. Average flow velocity curve of the pipeline outlet at different heights from the bottom.

The pneumatic lifting system lifting efficiency formula can be used to calculate and solve the pneumatic lifting efficiency η of pipelines with three different heights from the bottom and obtain the pneumatic lifting system efficiency curve shown in Figure 26 below. It can be seen from the figure that the efficiency of the pneumatic lifting system shows a decreasing trend as the height from the bottom increases. The efficiency of the pneumatic lifting system is the highest when the height from the bottom is 10 mm, at about 0.158. When the height from the bottom is 30 mm, the efficiency decreases significantly to about 0.108. It can be seen that for this pneumatic lifting pipeline system, an excessively large height of the water inlet from the bottom will cause a significant decrease in the efficiency of the pneumatic lifting system. At this time, the gas, liquid, and solid phases inside the pipeline will be unbalanced, resulting in the solid–liquid two-phase accumulation reducing the suction effect of pneumatic suction.

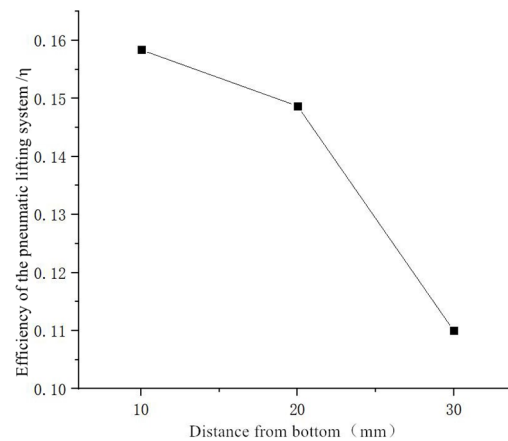


Figure 26. Pneumatic lifting system efficiency curve at different heights from the bottom.

4. Discussion

- (1) Particulate deposition dynamics were analyzed through numerical simulations, revealing transport characteristics under tank circulation. Particulate flow progresses through four phases: suspension, descent, sedimentation, and stabilization. At equilibrium: sedimentary particles: 26.7%; suspended particles: 14.5%; and turbulent particles: 58.8%.
- (2) Density and volume fraction contours illustrate gas–liquid–solid flow during pneumatic sediment removal, identifying four operational stages: initialization, pressure reduction, lifting, and stabilization. These visualizations elucidate internal flow characteristics throughout the multiphase transport process.
- (3) Parametric analysis demonstrates the impact of the port diameter (constant gas flow), showing that efficiency increases with the diameter, peaking at 0.16 (4 mm), as well as the impact of port quantity (constant flow/diameter), showing that efficiency decreases with additional ports, peaking at 0.158 (eight ports). Pipeline configuration and submersion depth critically influence sediment removal efficacy.

5. Conclusions

This study investigates gas–liquid–solid three-phase flow dynamics and structural impacts on sediment removal efficiency in pipeline-type pneumatic lift systems, establishing numerical foundations for underwater cleaning equipment optimization. Key findings indicate that, for optimal performance, an orifice diameter of 4 mm demonstrated optimal efficiency. Excessive water inlet ports should be avoided to prevent three-phase imbalance; when maintaining port quantities, the port spacing should be adjusted to enhance suction efficiency. System efficiency decreases with increasing submergence height, peaking at 0.158 (10 mm) but declining markedly to 0.108 (30 mm). An excessive height causes significant efficiency degradation due to disrupted three-phase equilibrium, promoting solid–liquid accumulation and impairing sediment removal capabilities. It is also important to note that the design of the airlift suction device should minimize disturbance to fish populations. Parameter design considerations must integrate fish swimming capabilities and benthic behaviors to optimize suction flow velocity/direction, minimizing biological disruption.

This research on the fish tank airlift sediment removal system establishes a universal research framework for cross-domain pneumatic transport systems through multiphase flow dynamics optimization and parameter design theory, with demonstrated applications in hazardous waste treatment and microalgae cultivation.

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