Investigation on water and air characteristics in Helicoidal Ramp Dropshafts

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ABSTRACT

Plunge dropshafts are widely used in urban drainage systems, but they can carry large amounts of air into the system, endangering the safety of the system. In this paper, a 3D numerical model is established to investigate the water flow configuration and air characteristics in a helicoidal ramp dropshaft. The simulations under different outlet pressures and water flow rates were simulated, and the results show that the air demand decreases with the increase of outlet pressure, especially in the case of low water flow. In the case of higher outlet pressure, the air demand first increases then decreases with the increase of the water flow rate. The dragging force of water has little effect on the pressure gradient in the dropshaft. The increase of ramp turns leads to the increase of terminal velocity at the same flow rate, and the air demand first increases and then decreases with the increase of ramp turns.

Key words: air demand, air pressure, helicoidal ramp dropshaft, water distribution

HIGHLIGHTS

- The water flow configuration and air entrainment in a helicoidal ramp type dropshaft was investigated.
- The air demand decreases with the increase of outlet pressure, especially in the case of low water flow.
- The increase of spiral turns leads to the increase of maximum velocity at the same flow rate, and the air demand first increases and then decreases with the increase of spiral turns.

1. INTRODUCTION

Dropshafts have been used widely in urban drainage systems to transfer stormwater or wastewater from a high elevation to deep trunks, accompanied by some air during the water falling process (Zhang et al. 2015; Ma et al. 2016). The air carried into tunnels can accumulate into large bubbles even air pockets, which may lead to the geyser in some severe cases (Stephenson & Metcalf 1991; Zhou et al. 2002; Vasconcelos & Wright 2006; Cong et al. 2017; Huang et al. 2018; Liu et al. 2022). The release of air may also cause sewer odor issues (Edwini-Bonsu & Steffler 2006). The momentum transfer from the falling water to the air is considered as the principal mechanism of air entrainment in the plunging dropshaft (Wei et al. 2018). Therefore, an important principle of designing the dropshaft is to minimize the amount of air discharged into deep tunnels (Kennedy et al. 1988).

There are two common types of dropshaft in urban drainage systems: plunge type (Rajaratnam et al. 1997; Ma et al. 2016) and vortex type (Jain & Kennedy 1983; Zhao et al. 2006; Hager 2010). Many studies have been carried out on the air entrainment in plunge dropshafts (Anderson & Dahlin 1975; Ervine & Falvey 1987; Chanson 2007; Granata et al. 2015; Granata 2016; Ma et al. 2018; Granata & Di Nunno 2022). The relative air demand, denoted by the ratio of the entrained air flow rate to the water flow rate (Ma et al. 2016), was different in different structures: about 1.4 in a dropshaft of 3 m high (Rajaratnam et al. 1997), about 40 in a dropshaft of 8 m high (Camino et al. 2015) and about 160 in a prototype dropshaft of 25 m high (Zhang et al. 2016). The air demand increases as the plunge dropshaft increases (Camino et al. 2015). The pressurized downstream and limited air inlet can reduce air demand (Granata et al. 2015; Ma et al. 2016; Wei et al. 2018), but reducing air demand to an acceptable level usually requires a larger air chamber between the dropshaft connection pipe and the tunnel. This will increase the investment of the project.

Jain & Kennedy (1983) made an exhaustive review of international experience in the design and performance of dropshafts, revealing that current practice strongly favors vortex type (spiral flow) dropshafts over those of the plunge type.
dropshaft. Kennedy et al. (1988) described a new kind of helicoidal ramp dropshaft, and the experimental results indicate that the new type of helicoidal ramp dropshaft is superior to other types of dropshafts both in their energy dissipation and air handling characteristics. The high efficiency of energy dissipation in the vortex drop structure even for a relatively small drop height (Zhao et al. 2006). The influence of inflow direction and flow rate on air demand in a helicoidal ramp dropshaft were investigated (Nobusawa et al. 2010; Weiss et al. 2010; Nakamura et al. 2015), however, the characteristics of the air inside the shafts and the air demand are not fully studied. These are important for studying the air entrainment requirements of shafts.

The helicoidal ramp shaft is better than the drop shaft in terms of reducing air demand, but its air pressure distribution and hydraulic characteristics are still not very clear. The primary objective of this article is to investigate the effect of the helicoidal ramp on air entrainment, pressure gradient, and water flow configuration in the helicoidal ramp dropshaft. A 3D numerical model was established based on an experimental setup (Kennedy et al. 1988), and the air demand under different outlet pressure and different water flow rates were simulated. The hydraulic characteristics of water and the variation of the pressure gradient in the shaft were analyzed, and the influence of ramp on flow rate and air demand was also investigated.

2. NUMERICAL METHODS

The geometry of the 3D numerical model with the detailed section is shown in Figure 1. The model mainly includes the inlet conduit, the air vent, the helicoidal ramp, and the outlet conduit connected to the dropshaft. The origin (x = 0, z = 0) was selected at the shaft bottom. The dropshaft has a diameter of 29.2 cm and a height of 1.5 m. The total height of the helicoidal ramp is 1.143 m, including 9 turns, and the height of each turn is 0.127 m. The helicoidal ramps are represented from top to bottom as turn1 to turn 9, respectively, see Figure 1(b). The slope of the inlet conduit is the same as that of the helicoidal ramp. The cross-section of the inlet conduit was a rectangle 12.7 cm high and 7.3 cm wide. The diameter of the outlet pipe connected with the dropshaft was 8.25 cm.

A dropshaft may contain one or more helicoidal ramps, and the dropshaft shown in Figure 1 contains dual ramps. The detailed section was shown in Figure 1(c) (Kennedy et al. 1988), where L is the vertical fall per turn; n is the number of ramps; p is the spiral pitch, p = L/n; d is the mean flow depth in the radial direction; ϕ is the mean ramp slope relative to horizontal (Kennedy et al. 1988); Ds is the dropshaft diameter; w is the normal width of each helicoidal ramp, w = pcosϕ; h is the ramp height in the radial direction.

The commercial software ANSYS CFX was employed for the numerical simulations. The water flow rate was defined at the inlet. All surfaces of the cylindrical block above the outlet and air vent were defined as atmospheric pressure. All other boundaries were set as no-slip walls. The no-slip wall boundary treats the velocity of the fluid at wall zero. The continuity equation and the Reynolds-averaged Navier-Stokes (RANS) equations are:

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0
\]

\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\frac{\partial \delta_{ij}}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(-\rho u_i u'_j\right)
\]

where: xi and xj are the Cartesian coordinates; ui and uj are the Reynolds averaged velocity components; ρ is the density of the fluid; p is the pressure; u′i and u′j are the fluctuating velocity components; δij is the viscous stress tensor component; t is the time.

The κ – ω based shear stress transport (SST) turbulent model and the volume of fluid (VOF) method (Hirt & Nichols 1981) were used to model turbulence and multiphase flow. The VOF method represents the volume fraction of each phase by adding variables α, which can be written as:

\[
\frac{\partial \alpha}{\partial t} + u_i \frac{\partial \alpha}{\partial x_i} = 0
\]

where: α is the volume fraction of water, where α = 1 represents water, and α = 0 represents air. The inhomogeneous two-phase flow model was utilized to simulate the flow where air and water flow fields were calculated separately.
Mesh independence analysis was conducted by comparing the air demand and water velocity in the dropshaft. Mesh refinement was made in the inlet conduit, outlet conduit air vent, and helicoidal ramps. The mesh numbers tested were 1.21, 1.57, and 2.05 million, and the simulation results are shown in Table 1. When the water flow rate is 8 L/s and at the height of

Figure 1 | Schematic diagram of the numerical model (Kennedy et al. 1988): (a) the helicoidal ramp dropshaft; (b) the central plane (z = 0); (c) the detailed section of the ramp.
0.828 m in the dropshaft, the water velocity under the 2.05 million mesh is 3.0% different from the velocity under the 1.57 million mesh, and the air demand difference is 4.3%. The model became meshing independent at about 2.05 million mesh where no significant improvement in water profile and air demand. Therefore, all the numerical simulations were based on the model with 2.05 million mesh.

Table 2 provides a summary of the simulation conditions. The outlet was pressurized in the experiment as an air chamber existed (Kennedy et al. 1988), so cases A are the conditions with different outlet pressures to verify the influence of outlet pressure on air demand and pressure distribution in the dropshaft. Six water discharges varying from 3.0 L/s to 17.0 L/s were simulated in cases A. The flow configuration of water is related to the ramp number (n), so the model of a single ramp is simulated in the case of B with five water discharges varying from 3.0 L/s to 13.5 L/s. The capacity of the dropshaft is closely related to the cross-section of the helicoidal ramp, and the ramp height is related to the ramp turns. Four ramp turns from 10 to 13 denoted as cases C1 to C4, respectively, were simulated to study the influence of different ramp heights on water velocity and air demand. One flow rate (8.0 L/s) was simulated in cases C conditions.

### Table 1 | Mesh independence analysis

| Mesh number (million) | Water velocity (m/s) | Water velocity relative error | Air demand (L/s) | Air demand relative error |
|-----------------------|----------------------|-------------------------------|------------------|--------------------------|
| 1.21                  | 1.82                 | /                             | 0.25             |                          |
| 1.57                  | 1.95                 | 6.7%                          | 0.22             | 12.0%                    |
| 2.05                  | 2.01                 | 3.0%                          | 0.23             | 4.3%                     |

3. RESULTS AND DISCUSSIONS

#### 3.1. Air demand and energy dissipation

In the dropshaft, water flows into the shaft in the tangential direction and down the helicoidal ramp, shown in Figure 2(a). Since there is no reverse force along the radius direction, the water keeps in contact with the sidewall, no matter how weak the centrifugal force becomes (Kennedy et al. 1988). When the water reaches the bottom of the shaft, a pool is formed. The pool partly covered the cross-section of the outlet pipe, and the water flows into the outer tunnel through the connecting pipe eventually. As the water flows down the shaft, an open core is formed in the center of the dropshaft, which is connected to the outside air pressure through the air vent.

The variations of air demand under different outlet pressures were compared with the experimental data (Kennedy et al. 1988), as shown in Figure 2(b). When the outlet pressure is lower (20 Pa), the simulation results are larger than the experimental results. With the increase of the outlet pressure (up to 100 Pa), the air demand at all flow rates showed a decreasing trend. At this point, the maximum air demand occurs when the flow rate is 8 L/s (about 4.8%). The air demands at the flow rate of 10.0 L/s and 13.5 L/s are in good agreement with the experimental data under this outlet pressure. With the further increase in the outlet pressure (300 Pa), the air demand is further decreased. When the flow rate is less than 8 L/s, the numerical

### Table 2 | Summary of simulated conditions

| Cases | Qw (L/s) | L (cm) | Turns | Outlet pressure (Pa) | n |
|-------|----------|--------|-------|----------------------|---|
| A1    | 3.0–17.0 | 12.70  | 9     | 20                   | 2 |
| A2    |          |        |       | 100                  |   |
| A3    |          |        |       | 300                  |   |
| B     | 3.0–13.5 | 12.70  | 9     | 20                   | 1 |
| C1    | 8.0      | 11.43  | 10    | 20                   | 1 |
| C2    |          | 10.39  | 11    |                      |   |
| C3    |          | 9.53   | 12    |                      |   |
| C4    |          | 8.79   | 13    |                      |   |
simulation results are consistent with the experimental data. However, the numerical simulation data are smaller than that of experimental measurement when the flow rate is greater than 8 L/s.

In the experimental process, the air was collected using an air bag through an air vent, and other air passages were sealed. The air demand in the dropshaft is determined by the time it takes to fill the air bag. The pressure inside the air chamber and the air bag is higher than the atmospheric pressure. In the process of air collection, the dragging effect of the water velocity is different, so the pressure in the air chamber is also different. The pressure in the outlet pipe changes with the flow rate. The air moves slowly at low flow rates, so larger pressure is needed to push the air into the air bag. The pressure required under a large flow rate is relatively small.

From the above results, the following conclusions can be drawn: (1) as the outlet pressure increases, the air demand decreases continuously; (2) in the case of larger outlet pressure, air demand increases first and then decreases with the increase of flow rate. When the water just flows into the dropshaft, the water velocity is small and the

Figure 2(c) shows the variation of the average cross-sectional depth of water in the dropshaft at different heights (along the radial direction, and the height is the center height of the cross-section), and Figure 2(d) shows the variation of the average cross-sectional velocity at different heights. In the experiment, Kennedy et al. (1988) measured the average cross-sectional depth in the ramp, and then obtained the average velocity of the cross-section based on the mass conservation, without the specific position of the measurement. When the water just flows into the dropshaft, the water velocity is small and the
cross-sectional area is large. As the water flows down the helicoidal ramp, part of the gravitational potential energy of the water turns to kinetic energy, so the water velocity increases and the cross-sectional area decreases. As the flow velocity increases, the force of friction also increases. When the gravity force of water in the direction of water flow is balanced with the friction force, the flow velocity does not continue to increase. The water continues to flow downwards at this velocity until it reaches the bottom pool, which is then drained out through the connecting outlet pipe.

The maximum velocity of water in the helicoidal ramp can be analyzed by the momentum theory. The control volume is taken as a small part of the water body in the ramp, and the water body is considered to be in direct motion. In the process of downward water flow, the main forces acting on the control volume are hydrodynamic pressure, gravity, and friction resistance. Since the control volume has no acceleration at equilibrium, all forces are in balance. Therefore, the force balance formula along the flow direction can be obtained

\[ F_{p1} - F_{p2} + G \sin \varphi - F_I = 0 \]  \hspace{1cm} (4)

where \( F_{p1}, F_{p2} \) are the dynamic water pressure of the upper and lower cross-sections, and \( F_{p1} = F_{p2} \) can be approximately assumed as the upper and lower cross-sections are equal. \( G \) is the gravity of the control volume, \( G = \rho g A l \); \( A \) is the cross-sectional area of the control volume, \( l \) is the length of the control volume, and \( \varphi \) is the slope of the helicoidal ramp; \( F_I \) is the friction resistance of the control volume, \( F_I = \tau_0 l \), \( \tau_0 \) is the average shear stress on the boundary, \( \tau_0 = f \rho v^2 / 8 \), \( f \) is the resistance coefficient.

The hydraulic radius of water in the ramp is (see Figure 1(c))

\[ R_h = \frac{wd}{w + 2d} \]  \hspace{1cm} (5)

Combined Equations (4) and (5), the maximum flow rate of water can be obtained

\[ v = \sqrt{\frac{8gwd \sin \varphi}{f(w + 2d)}} \]  \hspace{1cm} (6)

It can be seen from Equation (6) that the maximum flow velocity of water in the dropshaft is related to the wall roughness, the ramp slope, and the flow rate of water. The rougher the pipe wall leads to greater friction resistance and the smaller the maximum water flow rate. The ramp slope increases so that the component of gravity along the direction of the flow velocity is larger. Hence, a larger flow velocity is needed to produce a larger frictional resistance to balance the composition. So the steeper the ramp slope, the larger the maximum flow velocity. When the water flow increases, the cross-section area increases. The hydraulic radius is increased and the maximum flow velocity also increases. Both the numerical simulation data and the experimental results show that good results are obtained by the theoretical analysis.

To verify the energy dissipation level in the dropshaft, the energy of water flow in different sections was analyzed. The approach section 0 is at the inlet pipe, and the elevation of the floor is 1.32 m. Sections 1–8 are the cross-sections with different numbers of turns, and the elevation is the height of the center of the cross-section. Section 9 is at the outlet pipe, and the elevation of the section is 0.041 m.

It is assumed that the flow distribution in the dropshaft is axisymmetric and there is no axial flow (Jain 1987). The energy per unit of weight water on the horizontal section of the dropshaft, \( E \), is given by (Zhao et al. 2006)

\[ E = \frac{v_z^2}{2g} + \frac{v_t^2}{2g} + \frac{p(r)}{\rho g} \]  \hspace{1cm} (7)

where \( v_z \) is tangential velocity; \( v_t \) is tangential velocity; \( r \) is the radial coordinate; \( \rho \) is the density of water, and \( p(r) \) is the wall pressure. Therefore, the total head of water in the shaft is \( H = E + z \), where \( z \) is the elevation of each section. The flow at sections 0 and 9 was free surface flow and the water head in the section is \( H = h + v^2 / 2g + z \), where \( h \) is the water depth. The
energy dissipation efficiency of each part of the shaft can be obtained by

\[ \eta = \left(1 - \frac{H_{i+1}}{H_i}\right) \times 100\% \]  

(8)

where \( \eta \) is the efficiency of energy dissipation; \( H_i \) is the water head at section \( i \).

Figure 3(a) shows the energy dissipation efficiency between different connected sections and the pressure on the pipe wall. In the upper part of the dropshaft, the flow velocity is small, the pipe wall pressure is small due to the centrifugal force, and the energy per unit of weight water is small. When the water reaches the maximum velocity, the pressure on the pipe wall is almost the same, and the energy per unit of water is the same. The energy loss efficiency between the inlet pipe and section 1 is equal to \( \eta_{01} = 3.1\% \). Energy dissipation efficiency increases as water flow down. The energy dissipation efficiency between section 8 and the outlet pipe is about \( \eta_{09} = 65.3\% \). The total energy loss coefficient of the inlet pipe and outlet pipe is \( \eta_{09} = 85.3\% \). For water to flow into the dropshaft smoothly, the slope of the inlet pipe floor is the same as that of the helicoidal ramp, so the energy dissipation efficiency between the inlet pipe and section 1 is small. From section 1 to section 8, the drop height is 0.889 m, and the energy dissipation efficiency is \( \eta_{18} = 65.3\% \). The maximum energy loss occurs between section 8 and section 9. A pool is formed at the bottom of the shaft due to the annular velocity to effectively increase energy dissipation. Finally, the water flows out tangentially along the outlet pipe.

As the water flows down, the most amount of the water swirls downwards along the wall of the dropshaft, and an open core is formed in the center of the dropshaft. The process of airflow and pressure gradient in the dropshaft will be discussed later.

3.2. Air pressure distribution inside the dropshaft

Figure 4(a) shows the average pressure at different height sections of the dropshaft under different outlet pressures. It can be seen from the figure that the pressure change at the outlet has little influence on the pressure distribution in the dropshaft. The minimum pressure in the dropshaft appears on the section with the height of 1.34 m, and the maximum negative pressure value is about \(-0.5\) Pa. This is the height at which water enters the dropshaft through the inlet pipe. When the water enters the dropshaft, part of the air is dragged down by the water, thus forming a negative pressure area here. With the continuous decline of water, the pressure in the dropshaft presents a linearly increasing trend, and the pressure gradient is about \(1.45\) Pa/m.

Figure 4(b) shows the average pressure in different height sections of the dropshaft at different flow rates. As can be seen from the figure, when the flow rate in the dropshaft is different, the maximum negative pressure still appears at a place where water enters the dropshaft. The pressure in the dropshaft increases as the elevation of the dropshaft decreases. In the figure, the air pressure gradient in the dropshaft with different ramp numbers is compared: when \( n = 1 \), the pressure gradient in the

![Figure 3](http://iwaponline.com/wst/article-pdf/doi/10.2166/wst.2022.056/1004336/wst2022056.pdf) | Efficiency of energy dissipation in dropshaft \((n = 1, Q_w = 8\) L/s).
dropshaft changes greatly (4.59 Pa/m); when \( n = 2 \), the pressure gradient in the dropshaft is relatively small (1.45 Pa/m). The more the number of ramps in the dropshaft, the smaller the pressure gradient in the dropshaft.

The momentum law can be applied to analyze the pressure change in the dropshaft. The air at a height of one turn is used as the control volume for analysis, and the cross-section is taken as the area of the central core. The force exerted on this control volume mainly includes air pressure on the upper and lower cross-sections, gravity, friction resistance, and drag force of water flow. Since the control volume has no acceleration at equilibrium, all forces are in balance. Therefore, the vertical force balance formula can be obtained

\[-\Delta F + G + F_d \sin \phi - F_l = 0 \quad (9)\]

where \( \Delta F \) is the air pressure difference of the upper and lower sections of the control volume, \( \Delta F = \Delta P A_c \), \( A_c \) is the cross-sectional area of the control volume; \( G \) is the gravity of the control volume, \( G = \rho g A_c L \pi / 4 \), \( L \) is the length of the control volume; \( F_d \) is the drag force of the water on the air.

\[ F_d = \frac{1}{2} C_d \rho v^2 A_d \quad (10)\]

**Figure 4** | Pressure distribution in dropshaft: (a) average pressure variation under different outlet pressure; (b) average pressure variation under different flow rate.
where \( c_d \) is the drag coefficient \((c_d = 0.1, \text{Qian et al. (2016)})\); \( \Delta w \) is the difference in velocity between water and air; \( A_d \) is the interface area between water and air, approximated \( A_d = w\pi(D-2d) \).

\( F_f \) is the friction resistance acting on the control volume. Friction can be divided into two types: one is the friction between the airflow and the pipe wall, and the other is local pressure drop (e.g. through a reduced ramp). The force of friction can be expressed as

\[
F_f = \frac{1}{8} \rho_w v_w^2 A_e
\]

where \( A_e \) is the interface area between air and wall.

Substitute Equations (10) and (11) into Equation (9), which can be obtained after simplification

\[
\Delta P = \rho_w gL + 2C_d \rho_w \Delta w^2 \frac{w}{D-2d} \sin \varphi - \frac{1}{8} \rho_w v_w^2 A_e
\]

Equation (12) shows the average pressure change on the cross-section of the dropshaft in one turn. The three pressure gradient components are caused by gravity, water flow drag force, and frictional resistance, respectively. As can be seen from the equation, the gravity and drag force can increase the pressure gradient while frictional resistance decreases the pressure gradient. In the case of B1, when the water flow rate is 8 L/s, the increased air pressure caused by drag force is less than 0.1 Pa during one turn period, while the increased air pressure caused by gravity is about 1.5 Pa. Therefore, the dragging influence of water flow on air pressure is negligible compared with the influence of gravity. The variation of the pressure gradient in the dropshaft is mainly determined by gravity and friction, while water drag has little effect on the variation of the pressure gradient. This is different from the various factors of the pressure gradient in the plunge dropshaft (Ma et al. 2016). In the plunge dropshaft, the water flow that breaks into water droplets is dragging large amounts of air into the shaft, resulting in large air demand. And the larger the dropshaft, the greater the air demand (Camino et al. 2015).

Figure 5 shows the variation trend line of the average pressure on the central section of the dropshaft under different flow rates. The pressure gradient in the dropshaft increases with the increase of the flow rate: when the flow rate is 3 L/s, the pressure gradient is about 2.4 Pa/m; when the flow rate is 13.5 L/s, the pressure gradient is about 6.8 Pa/m. All of them are smaller than the pressure gradient increment under the action of gravity, so the effect of friction resistance on the pressure gradient is explained. The airflow in the dropshaft is mainly divided into two directions: one is the rotating flow down along the helicoidal ramp under the action of the water drag force. This part of the air is mainly concentrated at the interface with the water flow, and the velocity is relatively high. The other is an upward flow through the core at the center of the dropshaft. It can be seen from Equation (12) that the difference in pressure gradient in the dropshaft is mainly due to the different frictional resistance in the pipe. When the airflow velocity in the dropshaft is higher, more energy losses will be generated, so the pressure gradient is smaller. When the water flow rate is 3 L/s, the velocity of the circumferential air is about 2.0 m/s, and the vertical speed is about 1.0 m/s; when the water flow rate is 3 L/s, the speed of the circumferential air is about 1.62 m/s, and that of the vertical speed is about 0.9 m/s. When the water flow rate is small, the larger airflow rate results in greater energy loss, thus reducing the pressure gradient in the dropshaft.

### 3.3. Helicoidal ramp height

Cases C is the numerical simulations of the helicoidal ramp with different turns at the same height. The same flow rate \((Q_w = 8 \text{ L/s})\) is selected for the simulation. At the same height, the more the ramp turns, the smaller the ramp height and the smaller the ramp slope. Figure 6(a) shows the average flow velocity distribution under different turns. Under the same flow rate, the maximum flow velocity of the flow increases with the increase of ramp turns. The average depth at 9 turns was about 5.2 cm, and the maximum flow velocity was about 1.96 m/s; when the turns number is 13, the maximum average depth is about 4.2 cm and the maximum flow velocity is about 2.15 m/s. As the number of ramp turns increases, the wetter perimeter and water cross-section is decreasing, and the hydraulic radius of water flow is increasing. It can be seen from Equation (6) that the maximum flow velocity of the water increases with the increase of hydraulic radius.

Figure 6(b) shows the variation of air demand in the dropshaft with the increasing number of ramp turns. As can be seen from the figure, when the number of ramp turns is less than 11, the airflow rate increases continuously; while when the number of ramp turns is more than 11, the airflow rate drops sharply close to 0. As can be seen from the previous discussion,
when the water flow rate is 8 L/s, the air flows out of the dropshaft mainly through the effect of water entrainment. A smaller number of turns results in a smaller flow water velocity at the bottom of the dropshaft. As the number of ramp turn increases, the flow water velocity at the bottom of the dropshaft increases. The pool at the bottom of the dropshaft covers the outlet pipe, and the greater the flow rate, the better the sealing effect. When the flow rate exceeds a certain limit, a strict water curtain is formed at the inlet of the outlet pipe, which limits the air discharge. Therefore, under the same flow rate, when the number of ramp turns exceeds a certain number, the airflow rate will drop sharply to around 0.

4. CONCLUSIONS

In this paper, a three-dimensional numerical model was established to study the hydraulic dissipation and air demand of helicoidal ramp dropshaft. The calculated results are compared with the previous experimental data to prove the reliability and accuracy of the model. The simulation was carried out for different outlet pressures, and the relevant results showed that with the increase in outlet pressure, the air demand kept decreasing. In the case of larger outlet pressure, air demand increases first and then decreases with the increase of water flow rate. Larger outlet pressure with smaller water flow limited air concentration.

The change of water velocity in helicoidal ramps is analyzed by using the momentum theory. The rougher the ramp wall, the smaller the maximum water flow velocity. The airflow in the dropshaft has two flow directions: one is to spiral downward along the helicoidal ramp, and the other is moving up at the center core of the dropshaft. The pressure gradient caused by water dragging is much less than that caused by gravity. The influence of the ramp turn number on the flow velocity and air demand was also analyzed in this paper and found that under the same water flow rate, the maximum water velocity increases with the increase of ramp turns. The air demand increases first and then decreases as the number of turns increases.

As the experiment scale is relatively small, the scale effect has a great influence on the numerical simulation results. Moreover, the small outlet pipe limits the air outflow. Next, the researchers will build a larger scale model to study the hydraulic and air characteristics of the helicoidal ramp dropshaft.
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DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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Figure 6 | Water velocity and air demand at different ramp turn: (a) water velocity; (b) air demand.
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