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Design of Leachate Drainage System in Shallow Landfill Areas

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Abstract: Leachate drainage systems in landfills often face issues like pipe blockage and reduced seepage flow over time. Inadequate leachate drainage can lead to rising leachate levels in the waste heap, negatively impacting landfill gas collection efficiency. This study aimed to develop and test an air-lift device to improve leachate drainage in shallow landfills. The air-lift device was designed to lift leachate while allowing simultaneous landfill gas collection under negative pressure. Experiments examined how air pressure, submergence depth, pipe diameters, and lifting height affected the leachate outlet flow rate of the device. Orthogonal experimental analysis found submergence depth and lifting height had the most significant influence on outlet flow rate. A multiple regression model was developed to quantify the effects of these parameters. Additionally, a foam separator was incorporated into the device design and removed 20 - 30% of non-settleable particles from the leachate. While the foam separator improved leachate water quality, its effect on air quality requires further study. Overall, the air-lift device successfully lifted leachate and collected landfill gas simultaneously, providing an efficient alternative drainage method for shallow landfills.

Keywords: drainage system; foam separation; leachate

1 INTRODUCTION

The key to achieving harmless treatment and even resource utilization of municipal and rural waste is to ensuring the safe and stable operation of municipal landfills [1-3]. Effective drainage and harmless treatment of leachate improves the health and safety of garbage heaps in landfills and the recycling efficiency of energy gas. In addition, after advanced treatment, the leachate meets the water requirements for greening and flushing in the factory areas, achieving the recycling and utilization of water resources [4]. However, the traditional leachate drainage system adopts a passive drainage method, which is set up throughout the entire site, and consists of a gravel drainage layer and drainage pipe. The drainage system removes the leachate using gravity and is easily blocked. The concave filling method in plain landfills is more unfavorable for timely and safe drainage of leachate. If leachate is not drained in time, the drainage system can be blocked by the long-term accumulation of inorganic deposits and the large number of microbial biofilms. Poor drainage causes leachate to accumulate inside the heaps, which not only reduces their stability, but also leads to the tearing of the anti-seepage membrane due to uneven stress, thus causing the leachate to penetrate into the surrounding soil [5]. In addition, the rising leachate level in the garbage heaps also leads to poor drainage and unorganized overflow of landfill gas, which brings safety hazards to the site operation. At present, most landfills were built at the end of last century and the beginning of this century, and have entered the aging stage. On the one hand, the design and construction standards of these landfills are relatively low, and the anti-seepage, leachate drainage, and rainwater sewage diversion systems are incomplete, resulting in leakage and poor drainage of leachate and rainwater infiltration. On the other hand, long-term operation causes scaling and blockage in the lower leachate drainage system, which leads to the leachate level increase in the heaps and hinders the normal escape of landfill gas, thus posing safety hazards to the healthy and safety operation of the landfills, affecting the utilization of landfill gas, and also causing secondary pollution to the surrounding surface water, groundwater, and atmospheric environment [6]. In addition, shallow landfill piles produce large amounts of gas, and due to factors such as blockage of the leachate conduit system in the lower portion and the zoning cover impermeable layer, a high leachate level tends to form in the upper portion of the pile, thus affecting the discharge of landfill gas. Conventional leachate collection pumps can be used to convey and elevate the effluent generated from the waste, and often suffer from problems such as clogged pipes and reduced effluent collection seepage. In this paper, leachate air lifting method and device are developed to solve the original leachate lifting problem through the experimental study of three aspects: submergence depth, raising depth and air flow.

2 ANALYSES OF PROBLEMS IN THE LEACHATE DRAINAGE SYSTEM OF GARBAGE HEAP IN LANDFILLS

According to the "Technical Code for Municipal Solid Waste Sanitary Landfill", garbages should be landfilled in different areas and layers in the landfills. However, fresh garbages in the shallow landfills produce a large amount of leachate and landfill gas, whose drainage is particularly crucial, because the upper part of the landfills is directly in contact with the surrounding environment. Otherwise this can cause serious problems, such as secondary pollution of leachate, fire, explosion and odor pollution arising from unorganized emissions of the landfill gas. The traditional leachate drainage system is installed at the bottom of the entire landfills (Fig. 1), mainly including gravel drainage layer, diversion blind drain, and drainage pipe.

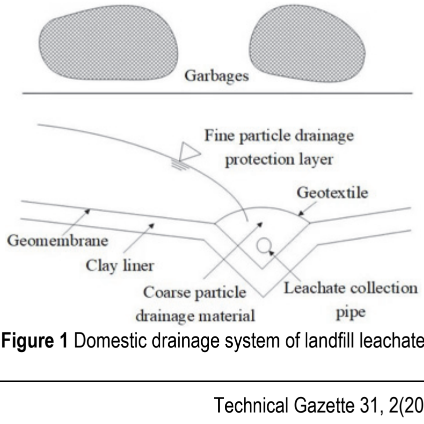

Figure 1 Domestic drainage system of landfill leachate

According to landfilling operation in different units and layers, garbages in each unit are landfilled; after phased landfilling in each operation area is completed, garbages are no longer landfilled in the area. The landfills, which have been in use for many years, have a layered structure, with regional differences in the distribution of leachate and landfill gas. Related literature has shown that urban landfills produce a large amount of landfill gas within 8 - 15 years and then a small amount of that later, considering the increase of moisture content in organic waste [7, 8]. The deep garbage heap has been landfilled for a long time, which produces a small amount of gas. Due to poor fluid permeability caused by dense covering layer, leachate drainage in this layer is almost the same as fluid extraction from confined aquifer. Garbage heap in shallow landfills produces a large amount of landfill gas. In addition, lower leachate drainage system is blocked, and impermeable layers are established in different areas, etc. High leachate level easily appears in the upper part, which affects the discharge of landfill gas [9, 10]. The landfill leachate gathers in the leachate diversion layer, and the main diversion pipe enters the leachate collection tank and then is pumped into the leachate treatment system of the landfills. On the one hand, some small sediments in the gravel layer often reduce or even block the pores of the drainage layer in actual operation, which weakens or disables its drainage function, causing the leachate level to rise in the landfilled garbage heap, thus threatening the stability of landfills [11, 12]. On the other hand, affected by the covering layer of lower landfills, the leachate infiltrates slowly, thus causing high leachate level in local areas, reducing the stability of local heaps and the space for gas generation, and serving as a water seal for the gas collection well, which is not conducive to the collection of landfill gas. In summary, the drainage of landfill leachate plays a crucial role in waste management. Currently, the research focus is on developing an efficient collection and drainage system for landfill leachate and gas, as well as a suitable system for lifting and transporting leachate under different working conditions. These advancements offer both social and economic benefits. However, two major issues exist in landfill drainage systems. Firstly, the submersible sewage pumps commonly used as lifting devices in landfills require frequent repairs due to blockages caused by high-concentration organic wastewater and large non-degradable objects like plastic bags and wires found in the waste. This poses safety hazards and increases operational costs by consuming manpower and reducing the service life of the pumps. Secondly, the existing sewage collection pipes have limited seepage flow, leading to inadequate leachate discharge. To address these problems, this paper proposes replacing the submersible sewage pumps with air-lift devices. Compared to lift pumps, air-lift devices have simpler pipes and do not require transmission or maintenance components, eliminating the need for power sources at lift points. This reduces the risk of gas leakage and blockages, ultimately saving operational costs [13-16]. The efficiency of the air-lift pump depends on several factors, including immersion ratio, inner diameter of the lift pipe, gas input/pressure, length of the lift pipe, viscosity of the lifting medium, lifting height, and number of air inlets. Additionally, the characteristics of the liquid being lifted and conveyed influence the flow pattern inside the lift pipe, thereby affecting the performance of the air-lift pump. Therefore, this paper aims to optimize the design of the leachate drainage system in shallow landfills by addressing the aforementioned aspects.

3 DESIGN AND EFFICIENCY STUDY OF LEACHATE DRAINAGE SYSTEM IN SHALLOW LANDFILLS

3.1 Design of Lift Device

This paper designed an air-lift device for lifting landfill leachate, including 1 garbage heap; 2 landfill gas collection pipe; 3 liquid lift pipe; 4 outlet of collected gas; 5 leachate outlet; 6 inlet of compressed gas; 7 water level indicator pipe; 8 foam separator and other structures; 9 liquid level inside the garbage heap. Cross-section structure of the device is shown in Fig. 2.

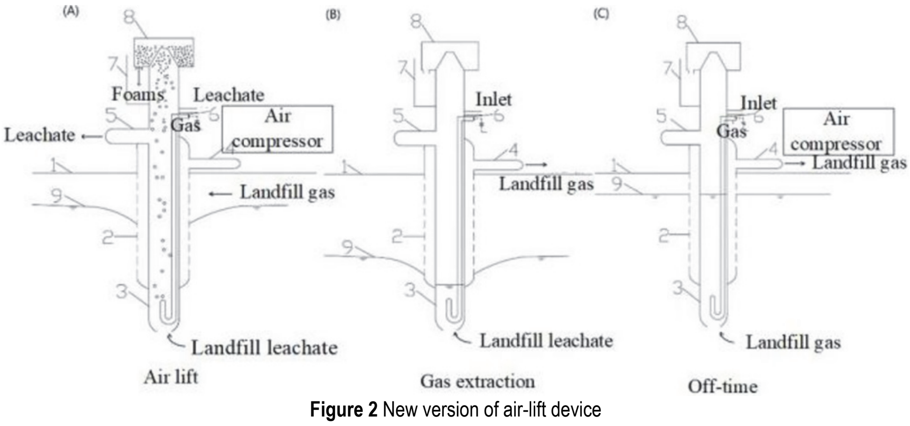

Figure 2 New version of air-lift device

The bottom of air-lift device collecting and lifting landfill leachate was the liquid lifting part, including liquid lift pipe, gas transmission pipe, and leachate collection pipe. The bottom end of the liquid lift pipe was open and immersed below the leachate surface. The gas transmission pipe was inside or outside the liquid lift pipe, and its outlet was near the lower end of the liquid lift pipe, which input compressed gas into the liquid lift pipe. The other end of gas transmission pipe opposite to the outlet was connected to the air compressor. When the gas transmission pipe was set inside the liquid lift pipe, the structure was simpler, and the gas transmission pipe was not affected by the internal structure and substances of the garbage heap, thus making the entire device operate more smoothly. One end of the leachate collection pipe was connected to the lower end of liquid lift pipe, and the other end was inserted into the garbage heap. With through holes or grooves set on the pipe wall, the leachate collection pipe was equipped with multiple extension pipes in different directions, which achieved horizontal and/or inclined extension. The central part of the device was to collect the landfill gas. There was a predetermined distance between the lower ends of both landfill gas collection pipe and liquid lift pipe. Part of the device also separated suspended particles of the leachate, which was at the top of liquid lift pipe, and set with a foam separator (Fig. 3), including a foam separator box and a conical part at the top of liquid lift pipe. Foam separator used bubbles to adsorb fine suspended solids or dissolved organic substances, thus achieving solid-liquid separation. The foam separator box had an opening at the bottom, which was used to put the box at the top of liquid lift pipe. The box had an opening on the bottom wall for discharging foams. Leachate outlet was set on the side wall of the liquid lift pipe at a predetermined distance below the separation part of suspended particles.

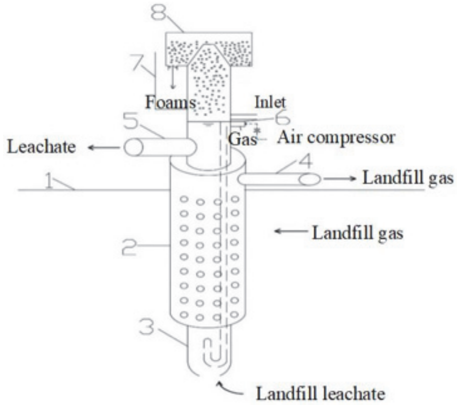

Figure 3 Combined device of foam separator and air-lift device
Note: 1. Garbage heap; 2. Perforated pipe with multiple holes; 3. Liquid lift pipe; 4. Outlet of collected gas; 5. Leachate outlet; 6. Inlet of compressed gas; 7. Water level indicator pipe; 8. Foam collector

The liquid lift pipe was immersed in the landfill leachate. Compressed air entered the liquid lift pipe through air pipe from the air compressor, and then turned into a gas-water mixture after mixing with the leachate, which had lower density compared with liquid outside the liquid lift pipe. In order to achieve balance, affected by the upward movement of bubbles and pressure, the liquid level inside the liquid lift pipe was higher than the external liquid level, thus lifting the liquid. Air lift of leachate caused the leachate level around the air-lift well to decrease and created a precipitation funnel, which reduced the water seal resistance of the landfill gas movement in the area, and maintained the leachate level always lower than the bottom of the perforated pipe with multiple holes, which was used for collecting landfill gas, during the gas collection process, thus achieving differential pressure and making gas collection more efficient. This device had multi-functions. The liquid lifting part maintained the leachate level at a certain height and below to reduce the water pressure on the impermeable membrane, thus ensuring the stability of garbage heap. At the same time, the air-lift device lifting the leachate was used to discharge the leachate in time, which enabled the leachate collection and lifting not to affect the collection and drainage of the landfill gas. The separation part of suspended particles used bubbles to absorb impurities for concentration, and suspended substances in the liquid were finally eliminated by removing the foams. Air in gas diffuser, which was set in the upper part of perforated pipe, brought impurities along with it to the liquid surface with the assistance of buoyancy. When more and more foams entered the foam collector and then discharged through the foam discharge pipe, the lifted leachate entered the regulating pool through the leachate outlet. This paper detected the turbidity change in the solution after using the foam separator. The leachate used in the experiment was taken from a landfill in Baoding, and the garbage had been landfilled for 20 years. Three sets of leachate samples were collected at different locations, with the following water quality indicators: turbidity of 59, 61, and 65, respectively; 800 ~ 1600 mg/L COD; 800 ~ 900 NH_4^+-N; 2 ~ 5 mg/L TP; 8 ~ 8.5 PH; chromaticity of about 2000, with brown color. The leachate turbidity after using foam separator was 44, 47 and 48 respectively. Calculation results showed that the removal rate of particles, which could not settle easily, using foam separator was about 20% ~ 30%, indicating that the foam separator separated suspended solid particles to a certain extent. But this may release dissolved pollutant gas in practical engineering applications. Compared with the foam separator, closed operation had more obvious positive impact on the surrounding environment of the landfills. The device not only lifted the leachate and collected landfill gas, but also stabilized the outlet water quality of the leachate and reduced the concentration of suspended solids in the outlet water, thus providing convenience for subsequent treatment and reducing the number of subsequent treatment facilities.

3.2 Study of the Drainage System Efficiency

No experiment has been conducted to examine the performance the air-lift device for landfill leachate. In order to analyze the working efficiency of the device in lifting leachate, this paper referred to the research results of Guo et al. [17], and selected several factors as variables, such as air pressure, submerged depth, inlet and outlet pipe diameter, thus investigating the lifting height and outlet flow rate of the device, and exploring the optimal operating conditions of the air-lift pump.

3.3 Experimental Equipment

The experimental materials used included glass column, air compressor, transparent rubber hose, scale ruler, etc. as shown in Tab. 1.

3.4 Experimental Scheme

This paper first made single factor experimental analysis to identify key influencing factors of outlet flow rate, and then made full factor variance analysis through orthogonal experiment to obtain the optimal flow rate maximization conditions. Finally, MATLAB was used to fit the dynamic equation to establish a leachate air-lift drainage model.

Table 1 Main experimental equipment

Name	Model/specification	Manufacturer
Silent oil-free air compressor	BD-550 × 2-50L	Taizhou Beide Electromechanical Co., Ltd.
Rubber hose	12 mm × 8 mm	KGKPU, Taiwan
Air pipe	5 mm × 8 mm	KGKPU, Taiwan
Pure/ultra pure water manufacturing system	UPH-I	Xi'an Youpu Instrument & Equipment Co., Ltd.
Six link constant temperature water bath asynchronous electric stirrer	HJ-6S	Jintan Youlian Instrument Research Institute
Digital display constant temperature magnetic stirrer	85-2A	Jintan Jieruier Electric Appliances Co., Ltd.

Table 2 Design of factors and levels in orthogonal experiment

Item	Factor	Level 1	Level 2	Level 3	Level 4
Air pressure / MPa	Factor 1	0.1	0.12	0.14	0.16
Submerged depth	Factor 2	0.4	0.8	1.2	1.6
Outlet pipe diameter / mm	Factor 3	25	32	40	50
Inlet pipe diameter / mm	Factor 4	8	10	12	16
Outlet water height / m	Factor 5	3	4	5	6

Table 3 Design of orthogonal experiment

Test No.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

The single factor experimental design was as follows. The first set of experiments considered the impact of air pressure (gas flow rate) on the outlet flow rate and investigated the outlet flow conditions under different gas flow rates, namely, 0.8 m submerged depth, 10 mm inlet pipe diameter, 40 mm outlet pipe diameter, 3 m lifting height, and air pressure at 0.06 MPa, 0.1 MPa, 0.14 MPa, 0.18 MPa, and 0.22 MPa, respectively. The second set of experiments investigated the impact of submerged depth on the outlet flow rate, under the conditions of 0.2 MPa air pressure, 10 mm inlet pipe diameter, 40 mm outlet pipe diameter, 3 m lifting height, and submerged depth of 0.2 m, 0.4 m, 0.6 m, 0.8 m, 1.0 m, 1.2 m and 1.4 m. The third set of experiments investigated the impact of different gas inlet methods on the outlet flow rate, and analyzed the relationship between the inlet pipe diameter and the water flow rate, under the conditions of 0.1 MPa air pressure, 0.8 m submerged depth, 40 mm outlet pipe diameter, 3 m lifting height, and inlet pipe diameters of 8 mm, 10 mm, 12 mm and 16 mm. The fourth set of experiments summarized the impact of outlet pipe diameter on outlet flow rate, under the conditions of 0.1 MPa air pressure, 10 mm inlet pipe diameter, 0.8 m submerged depth, 3 m outlet water height, and outlet pipe diameters of 28 mm, 32 mm, 40 mm, 50 mm and 75 mm. The fifth set of experiments aimed to clarify the impact of lifting height on the outlet flow rate, under the conditions of 0.2 MPa air pressure, 1 m submerged depth, 12 mm inlet pipe diameter, 25 mm outlet pipe diameter, and lifting heights of 4 m, 5 m, 6 m, 7 m and 8 m, respectively. Since the leachate discharged was pulsed, there may be errors in the measurement of leachate discharge using a flow meter. Therefore, in this experiment, the outlet flow rate was measured by using a cylinder container to collect the leachate excluded for a certain period of time, and then the flow rate was calculated to get the outlet flow rate during the period of time. Analysis of orthogonal experiment: the experiment aimed to examine the combined effects of the above single factors, as shown in Tab. 2 and Tab. 3. Factors 1, 2, 3, 4 and 5 in the table were air pressure, submerged depth, outlet and inlet pipe diameter, and lifting height, respectively.

4 RESULT ANALYSIS

4.1 Single Factor Variance Analysis

(1) Impact of input air pressure (air volume).

Under the conditions of 0.8 m submerged depth, 10 mm inlet pipe diameter, 40 mm outlet pipe diameter, 3 m lifting height, and 0.06 - 0.22 m^3/h air flow rate, the outlet flow rates are shown in Tab. 4 and Fig. 4. The results showed that outlet flow rate per unit time increased along with the increase of air pressure (air volume). When the air pressure (air volume) was small, the change in unit air pressure caused a significant change in outlet flow rate. When the air pressure increased to 0.14 MPa, any further increase almost did not change the outlet water rate, which tended to stabilize. The outlet flow rate under the pressure of 0.22 MPa slightly decreased compared with that under the pressure of 0.18 MPa. As a whole, with the change of air pressure, the outlet flow rate increased rapidly, then had a smaller growth rate, and finally decreased, because low gas inlet volume caused bubble flow in the liquid lift pipe and low outlet flow rate. As the gas inlet volume increased, the gas-liquid two-phase flow in the liquid lift pipe gradually turned into slug flow, causing the outlet flow rate to increase. As the gas inlet volume continued to increase, the gas-liquid two-phase flow pattern became unstable, resulting in a decrease in outlet flow rate.

Table 4 Outlet flow rates at varying input air pressures (air volumes)

No.	Air pressure	Outlet water rate / L	Time / s	Outlet flow rate / L/min
1	0.06	1.95	16.87	6.935388
2	0.1	2.8	20.95	8.019093
3	0.14	3.95	22.5	10.53333
4	0.18	2.45	13.93	10.55276
5	0.22	2.8	15.98	10.51341

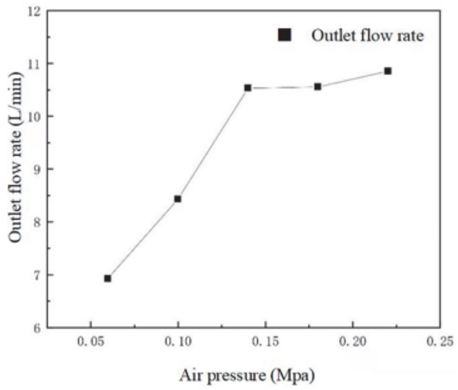

Figure 4 Outlet flow rates at varying air pressures

(2) Impact of submerged depth.

Under the conditions of 0.2 MPa air pressure, 10 mm inlet pipe diameter, 40 mm outlet pipe diameter, and 3 m lifting height, the water flow rates at different submerged depths are shown in Tab. 5 and Fig. 5.

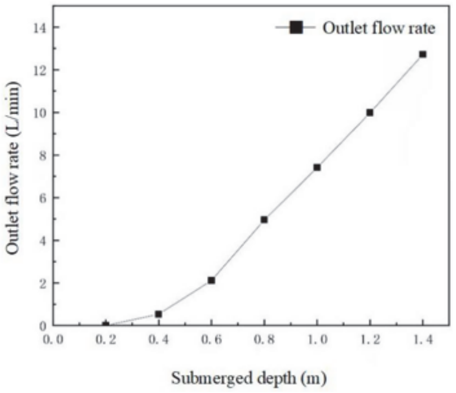

Figure 5 Outlet flow rates at varying submerged depths

Table 5 Outlet flow rates at varying submerged depths

No.	Submerged depth / m	Outlet water rate / L	Time / s	Outlet flow rate / L/min
1	0.2	0	3.74	0
2	0.4	0.15	16.7	0.538922
3	0.6	0.7	19.78	2.123357
4	0.8	1.6	19.36	4.958678
5	1	2.4	19.4	7.42268
6	1.2	3.45	20.71	9.995171
7	1.4	4	18.85	12.7321

Change in submerged depth caused the change in the differential pressure inside and outside the air-lift device, which in turn affected the outlet flow rate of lifted liquid. Data showed that too small differential pressure caused no outlet flow rate when the submergence depth was or less than 0.2 m. As the submerged depth increased, the outlet flow rate gradually increased. When the submerged depth exceeded 0.6 m, clear linear relationship occurred between it and the outlet flow rate. Under this working condition, the relationship between outlet flow rate and submerged depth was fitted using the following equation, with fitting accuracy R^2 up to 0.9995.

$$y = 2.6254x - 5.6806 \tag{1}$$

The increase in submerged depth increased the driving head lifting the leachate. When other conditions remained unchanged, the outlet flow rate continuously increased with the increase in submerged depth. It can be explained that to make the leachate rise to a certain height, there must be a certain depth of submergence and a certain amount of compressed air needs to be supplied to form a certain value of the density of the water-vapor solution in the lifting tube. The greater the rising height of the water vapor solution, the smaller its density should be, the greater the amount of air to be consumed, and the greater the submergence depth. Therefore, the submergence depth is a direct influence on the lifting height value.

(3) Impact of inlet pipe diameter.

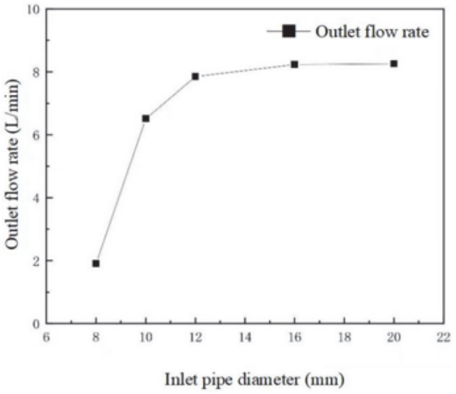

Figure 6 Outlet flow rates at varying inlet pipe diameters

Under the conditions of 0.1 MPa air pressure, 0.8 m submerged depth, 40 mm outlet pipe diameter, and 3 m lifting height, the variation of outlet flow rate along with inlet pipe diameter is shown in Tab. 6 and Fig. 6. The experiment results showed that the outlet flow rate increased with the increase of the inlet pipe diameter. When the diameter increased from 8 mm to 10 mm, the largest increase of outlet flow rate occurred. As the diameter continued to increase, the growth rate of outlet flow rate gradually slowed down. Under the conditions of 16 mm and 20 mm pipe diameters, the outlet flow rate remained basically unchanged. Small inlet pipe diameter caused small gas-water mixing interface and rapid gas upward movement, resulting in insufficient mixing and low air-lift efficiency. Diameter increase extended the gas-water mixing interface at the inlet end, which rapidly released the instantaneous mixing pressure, slowed down the upward gas movement speed, and increased the mixing time, thus making the gas-water mixture more complete, and improving the leachate lifting efficiency.

Table 6 Outlet flow rates at varying inlet pipe diameters

No.	Inlet pipe diameter / mm	Outlet water rate / L	Time / s	Outlet flow rate / L/min
1	8	0.85	27.01	1.88819
2	10	2	18.47	6.497022
3	12	1.95	14.89	7.857623
4	16	2	14.56	8.241758
5	20	2.06	14.97	8.256513

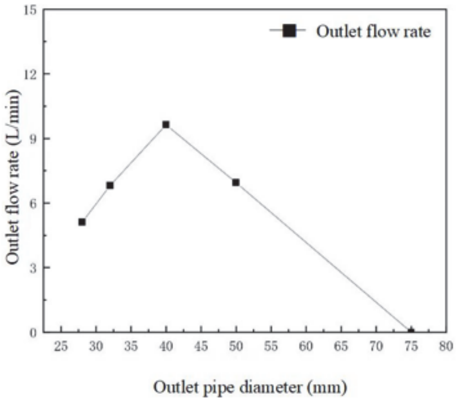

Figure 7 Outlet flow rates at varying outlet pipe diameters

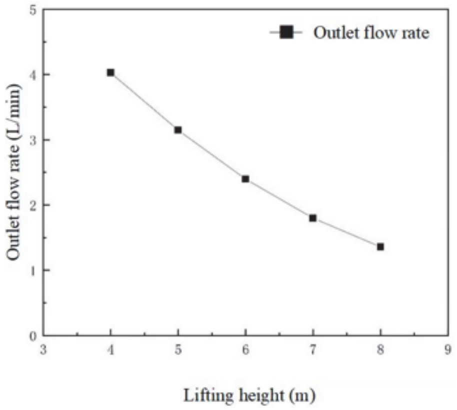

Figure 8 Outlet flow rates at varying lifting heights

Table 7 Outlet flow rates at varying outlet pipe diameters

No.	Outlet pipe diameter / mm	Outlet water rate / L	Time / s	Outlet flow rate / L/min
1	28	1.7	20	5.1
2	32	2.3	20.26	6.811451
3	40	2.6	16.2	9.62963
4	50	2.55	22.05	6.938776
5	75	0	17.59	0

Table 8 Outlet flow rates at varying lifting heights

No.	Outlet water height / m	Outlet water rate / L	Time / s	Outlet flow rate / L/min	Average outlet flow rate / L/min
1	8	0.47	21.43	1.315912	1.3504648
2	8	0.53	22.96	1.385017	
3	7	0.6	20.19	1.783061	1.7982527
4	7	0.58	19.19	1.813445	
5	6	0.74	18.76	2.366738	2.3931698
6	6	0.79	19.59	2.419602	
7	5	0.95	18.04	3.159645	3.1456194
8	5	0.94	18.01	3.131594	
9	4	1.3	19.22	4.058273	4.0260641
10	4	1.3	19.53	3.993856	

(4) Impact of outlet pipe diameter.

Under the conditions of 0.1 MPa air pressure, 10 mm inlet pipe diameter, 0.8 m submerged depth, and 3 m outlet water height, the variation of outlet flow rate along with outlet pipe diameter is shown in Tab. 7 and Fig. 7.

Analysis of experimental data showed that outlet water rate increased with the increase of outlet pipe diameter when the diameter was less than 40 mm. When the diameter was greater than 40 mm, the outlet water rate decreased with the increase of the diameter. In a certain range, the increase in the diameter of the outlet pipe can significantly enhance the device's export flow, but with the increase in pipe diameter you have an extreme value; in the experiment, this value was about 40 mm, more than this extreme value of the enhancement of the amount will not rise rather than fall. As a result of the large diameter outlet pipe in order to achieve the same amount of liquid outflow with a small diameter requires greater heating power, resulting in lower efficiency of the device.

(5) Impact of lifting height.

Under the conditions of 0.2 MPa air pressure, 1 m submerged depth, 12 mm inlet pipe diameter, and 25 mm outlet pipe diameter, the variation of outlet flow rate along with the lifting height is shown in Tab. 8 and Fig. 8. The data showed that the outlet water rate decreased with the increase of lifting height, which very well complied with the exponential function relationship. The following equation was used for fitting, with the fitting accuracy R^2 at 0.9991.

$$y = 5.3811e^{-0.274x} \tag{2}$$

4.2 Orthogonal Experiment

Intuitive analysis of the orthogonal experiment results is shown in Tab. 9. According to the range analysis results in Tab. 9, the primary and secondary order of various factors affecting the results is submerged depth > outlet water height > outlet pipe diameter > inlet pipe diameter > air pressure.

Table 9 Intuitive analysis of orthogonal experiment results of multiple factors affecting outlet water rate

No.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Outlet water rate / L/min
1	1	1	1	1	1	0.52
2	1	2	2	2	2	0.11
3	1	3	3	3	3	0
4	1	4	4	4	4	0
5	2	1	2	3	4	11.7
6	2	2	1	4	3	3.6
7	2	3	4	1	2	1.5
8	2	4	3	2	1	0.2
9	3	1	3	4	2	75.4
10	3	2	4	3	1	16.5
11	3	3	1	2	4	6
12	3	4	2	1	3	2.6
13	4	1	4	2	3	36.6
14	4	2	3	1	4	7.5
15	4	3	2	4	1	33.2
16	4	4	1	3	2	10.7
Range	4.725	16.750	6.350	5.300	8.700	

Table 10 Variance analysis of orthogonal experiment results

Factor	DEVSQ	Degree of freedom	*F* ratio	*F* critical value
Air pressure	53.325	3	0.254	3.290
Submerged depth	635.845	3	3.023	3.290
Outlet pipe diameter	87.615	3	0.417	3.290
Inlet pipe diameter	65.625	3	0.312	3.290
Outlet water height	209.220	3	0.995	3.290
Error	1051.630	15		

According to the variance analysis of orthogonal experiment results (Tab. 10), the impact of submerged depth and lifting height on the outlet flow rate is significant, which is consistent with relevant research results. In theory, gas flow rate has a significant impact on the outlet flow rate while the results of this orthogonal experiment showed that the impact of air pressure was not significant, mainly because the air pressure range designed in the experiment was small.

4.3 Leachate Air-Lift Drainage Model

Fluid conveying capacity of air-lift device was related to various factors. There have been few researches on the lifting characteristics of the device. In 1968, Stenning and Martin used the gas-liquid slip rate to correlate the gas-liquid two-phase characteristics, and proposed a one-dimensional model to describe the relationship between gas flow rate and the lifted liquid flow rate. Parker improved the one-dimensional model by considering the influence of gas flow rate at the nozzle on liquid flow, which was further verified by Khalil experiment. The modified model was as follows:

$$\frac{H}{L}-\frac{1}{1+\frac{1}{S}\cdot\frac{Q_g}{Q_L}}=\frac{Q_L^2}{2gLA^2}\cdot\left[(K+1)+(K+2)\frac{Q_g}{Q_L}-2\frac{\rho_g}{\rho_L}\cdot\left(\frac{Q_g}{Q_L}\right)^2\right] \tag{3}$$

where, H/L is the submerged degree of air-lift pump, S is the ratio of air flow rate to liquid flow rate Vg/VL, called slip rate, K is the friction parameter $(4fL')/D'$, and F is the friction factor. Zhang and other scholars found through experiments that when the submerged degree was less than 0.4, the Parker model had a large error in describing the experimental results of high-viscosity liquid, and could not describe the characteristics of air-lift pump with high viscosity and low submerged degree [18-21]. In experimental research on the performance of low lift air-lift pump below 3 m, Guo et al. [17] described the relationship among the lifted water flow rate (Q), air flow rate (q), submerged depth (h), and lifting height (H) of the pump, and constructed a single factor model between each factor and flow rate. By changing the three parameters one by one, namely, air flow rate, submerged depth, and lifting height, the research studied the relationship between them and the lifted water flow rate of the pump:

(1) Under the premise of 70 cm submerged depth and 26 cm lifting height, the water flow rate Q lifted by the air-lift pump was directly proportional to the air flow rate q. The relationship equation was:

$$Q=6.4679q-23.217 \tag{4}$$

(2) Under the premise of 6 m^3/h air flow rate and 26 cm lifting height, the lifted water flow rate Q increased with the increase of the submerged depth h, and the relationship equation was:

$$Q=4\cdot10^{-22}h^{12.315}\left(50\text{ cm}\le h\le 70\text{ cm}\right) \tag{5}$$

(3) Under the premise of 6 m^3/h air flow rate and 70 cm submerged depth, the lifted water flow rate Q decreased with the increase of lifting height H, and the relationship equation was:

$$Q = 1.1394H + 51.06 \tag{6}$$

Obviously, the above two description methods could not effectively describe the working characteristics of the air-lift device in this experiment. Therefore, MATLAB was used for statistical analysis based on statistical data. The fitted multiple linear regression model is shown in Eq. (7):

$$\begin{aligned} y = & -48.75X_1 + 13.6625X_2 + 0.192646X_3 + \\ & +0.38857X_4 - 2.37X_5 \end{aligned} \tag{7}$$

where, X_1 is the air pressure (MPa), X_2 is the submerged depth (m), X_3 is the outlet pipe diameter (mm), X_4 is the inlet pipe diameter (mm), and X_5 is the lifting height (m).

5 CONCLUSIONS

Based on the leachate drainage problem, this paper proposed and developed an air-lift method and implementation device for leachate. Orthogonal experiment was conducted to examine the performance of the leachate air-lift drainage device. The results showed that the submerged depth and lifting height were the most significant factors affecting the outlet flow rate. Based on theoretical analysis and experimental results, this paper obtained a multiple regression model for the leachate air-lift drainage system, and quantitatively analyzed the impact of several factors on the working characteristics of the air-lift device, i.e., submerged depth > outlet water height > outlet pipe diameter > inlet pipe diameter > air pressure. In addition, it was found that the foam separator helps solid-liquid separation and stabilizes water quality. The experiment results showed that the foam separator removed about 20% ~ 30% particles, which could not settle easily. The development of a new leachate drainage system is important for the safe and stable operation of landfills. By optimizing the combination of leachate and landfill gas conduction and drainage systems, and exploring the efficient treatment of leachate, breakthroughs have been made in three aspects: landfill health operation risk, liquid and gas synergistic conduction and drainage, and treatment. The results of the study can be used to guide the engineering practice, and at the same time to improve the health and safety operation level of the plain landfill and the utilization of secondary pollution resources.

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