Gas state equation and flow mechanism of gas–liquid two-phase flow in airlift pump system

Yanlian Du (杜燕连) ; Jingyu Zhu (朱井育); Xuanhe Han (韩煊赫) ; Mengdi Fu (符孟帝) ; Meng Li (李萌); Yijun Shen (沈义俊)
Gas state equation and flow mechanism of gas-liquid two-phase flow in airlift pump system

Yanlian Du, Jingyu Zhu, Xuanhe Han, Mengdi Fu, Meng Li, and Yijun Shen

AFFILIATIONS
1 School of Information and Communication Engineering, Hainan University, Haikou 570228, China
2 State Key Laboratory of Marine Resources Utilization in South China Sea, Hainan University, Haikou 570228, China
3 College of Mechanical and Electrical Engineering, Hainan University, Haikou 570228, China
4 School of Marine Science and Engineering, Hainan University, Haikou 570228, China

ABSTRACT
Airlift pumps (ALPs) have a simple structure and significant application potential. However, previous studies on ALPs have generally assumed that the gas density remains constant. In this paper, the gas state equation (GSE) for ALP is established based on the van der Waals formula, which explicitly considers the density of gas. An electrical resistance tomography system is used to collect the gas void fractions at different heights under different gas flow rates, and an empirical formula for the gas void fraction is established. To verify the effectiveness of the proposed model, high-precision pressure sensors and a high-speed camera are used alongside an electrical resistance tomography system to determine the realistic ALP flow parameters. The results of 409 sets of experiments show that: (1) the gas in ALP cannot be regarded as ideal gas, because the ideal GSE cannot distinguish between different gas flow rates; (2) the state change of gas in ALP is a quasi-equilibrium process, whereby the GSE of ALP can be obtained from the pressures under several locations; (3) the axial pressures predicted by the proposed GSE for ALP are in good agreement with experimental data; and (4) a single parameter of the GSE uniquely determines the state process. The proposed model and the experimental data provide a new methodology and comprehensive references for studying the working mechanism and efficiency of ALPs.

I. INTRODUCTION
Airlift pumps (ALPs) are pump-based riser systems in which air is applied as a power source. They are typically composed of a vertical pipe with a special structure, which is partially dipped into a liquid/slurry that is to be lifted, whereupon gas is injected near its base. When gas is injected into the lower part of the tube, the gas rises as bubbles due to its low density. As the bubbles rise, they either break up or coalesce. The vacuum caused by the rise in bubbles sucks up the liquid/slurry at the bottom of the tube, resulting in a pump action. Compared with traditional pumps, ALPs have many advantages, e.g., no moving parts, no wear problems, simple mechanics, low manufacturing and maintenance costs, low shear force, and no contact in the upriser. Since their original development by Loscher as a lightweight lifting device, ALPs have been employed to transport fluids and slurries in the field of aquaculture, nuclear fuel reprocessing, sediment removal, special chemical fluids, airlift reactors, carbon fuel cell systems, nutrient-rich deep-sea water, and deep-sea mining. To date, researchers have accumulated significant theoretical and experimental research on ALPs, mostly relating to the effects of operating parameters and geometric parameters on the capability and efficiency of the system. Kassab et al. performed a series of experiments at nine submergence ratios on three lifting tubes of different lengths. Their results show that the pump capacity and efficiency are functions of the air mass flow rate, submergence ratio, and length of the lifting tube. The best efficiency range was found to be in slug and slug-churn flow regimes. Zhong et al. studied the performance of a
large-diameter ALP and found that the flow pattern was an important factor affecting its performance in shallow operating depths. Fan et al.\textsuperscript{10} experimentally and theoretically analyzed the key factors that affect the efficiency of ALPs. Their results suggest that larger pipe diameters result in higher efficiency by introducing more kinetic energy and more power from the surface of water, and indicate that surface tension effects are negligible when the pipe diameter is greater than 20 mm, as proved by Reinemann et al.\textsuperscript{13}. Based on the one-dimensional theory, Stenning and Martin\textsuperscript{16} analytically and experimentally studied the effects of various parameters on ALP systems, including the air flow rate, water flow rate, submergence ratio, axial pressure distribution, friction factor, and slip ratio. However, in their calculations, they considered the pipe as a whole and neglected changes in air density along the flow direction. Catrawedarma et al.\textsuperscript{1} presented a comprehensive review of the literature on both air–water two-phase and air–water–solid three-phase ALPs. They divided the influencing parameters into geometric and operational categories. The first type included the submergence ratio, pipe diameter and length, design, and air injector position, while the second category considered the testing fluid, particle diameter and density, and the injected volume flow rate of air. They presented detailed derivations of ALP equations and experimentally studied the effects of each parameter. Kassab et al.\textsuperscript{22} studied the performance of five ALPs with variable cross sections, e.g., riser with equal cross section, one-step and two-step enlarged pipes, and one-step and two-step contracted pipe uprisers.

In addition to research on the effects of geometry and operational parameters of ALPs, several studies have examined the working mechanism and state process of ALPs. Shimizu et al.\textsuperscript{11} proposed a mathematical model for predicting the state of a non-Newtonian fluid inside an ALP. However, the proposed mathematical model failed to predict the velocity of the mixture at the outlet. Based on the drift flux model and modified Akawa pressure-drop equation, Liu and Yao\textsuperscript{1} proposed a mathematical model for predicting the steady-state and unsteady-state conditions of a non-Newtonian fluid (rare earth mud) in ALP. Comparisons with experimental data showed high precision and good predictions of flow rates at the outlet in both the steady and unsteady states. Hanafizadeh et al.\textsuperscript{26} found that the amplitude of the pressure fluctuations depends on the flow regime, particularly the level of turbulence and flow heterogeneity. Some researchers have introduced methods for identifying the flow regime based on the pressure fluctuations in the gas–liquid flow.\textsuperscript{20,21} Sun et al.\textsuperscript{22} distinguished the gas–liquid flow patterns from the wavelet packet energy entropy obtained from the decomposed pressure signals and reported an identification rate of 92.86%, which is suitable for most engineering applications.

Catrawedarma et al.\textsuperscript{1} designed a special bubble generator to suck atmospheric air in and produce uniform-sized and evenly distributed bubbles in the riser pipe using pressurized water from a water pump. They claimed that the probability density function of the differential pressure became wider as the superficial air velocity increased, because an increase in air velocity resulted in greater coalescence and breakup of bubbles. As the initial size and distribution of the bubbles become more uniform, the system became more efficient. Based on energy conservation and the phase holdup equations, Wang et al.\textsuperscript{24} analyzed the relationship between the pressure drop and pipe diameter of ALP. They reported that an increase in pipe diameter produced a precipitous drop in pressure at first, which then stabilized, although this has not been experimentally validated. They treated the air inside the pipe as an ideal gas and calculated the gas void fraction as the ratio of gas flow rate to water flow rate. However, this is not correct, because the density difference of air along the flow passage cannot be neglected under long-distance transport, e.g., deep-sea mining. Takano et al.\textsuperscript{25} reviewed previous studies for two- and three-phase flows, including slip flow models and drift flux models of the void fraction, homogeneous models, and separated flow models of frictional pressure drop. They proposed methods for estimating the void fraction and frictional pressure drop in three-phase flow that involve fewer constants and are applicable to a wider range of conditions than existing correlations. Smith\textsuperscript{26} proposed a void fraction correlation based on the slip model for annular flow and claimed that this correlation could be used in other flow regimes. Woldesemayat and Ghajar\textsuperscript{27} summarized the void fraction correlations of two-phase flows in the literature and divided them into four categories: (i) slip ratio correlations, which are functions of the ratio of the air flow rate to the total; (ii) $K_{eq}$ correlations, which are products of a flow parameter $K$ and the homogeneous void fraction $e_{eq}$; (iii) drift flux correlations, which consider the nonuniformity of the flow captured through a distribution parameter and the drift velocity; and (iv) general void fraction correlations, which are empirical in nature and incorporate the basic underlying physical principles into different physical parameters. However, most correlations have primarily been developed for nonvertical uprisers and are limited to a particular flow pattern, although some have been designed for vertical flows and inclined cases and are claimed to work in other flow patterns. These correlations have not been tested experimentally. Based on a one-dimensional multifluid model, Rim et al.\textsuperscript{28} carried out numerical analyses of multiphase steady flow in ALPs. The axial distributions of eight physical quantities were calculated by solving the governing equations, including the void fractions and velocities of each phase, the air density, and the pressure drop. However, the air was assumed to obey the ideal gas state equation (GSE).

Many experimental techniques have been employed to better understand the flow process of ALPs, such as pressure probes, pressure sensors, differential pressure sensors, fiber optic probes, electrical resistivity technology, and high-speed cameras. Pressure measurements are commonly used for two main reasons. First, pressure sensors are easy to install, and once installed, pressure data can be acquired in real time. They are also highly accurate and relatively cheap. Second, the axial pressure distribution directly reflects the state and distribution of the multiphase fluid inside. Because gas is compressible, the gas and liquid are likely to flow in response to changes in pressure. The axial pressure distribution is therefore expected to contain sufficient information on the flow characteristics.

To date, the working mechanism and flow process of ALPs remain unclear. Unless they are thoroughly understood, any research on how the geometric or operating parameters affect the efficiency of the system is necessarily crude, and the effects may be different than expected. The prediction of the void fraction of each phase, the relationship of the gas state, and the axial pressure distribution are vital components characterizing ALP systems. Once these are known, the flow process in the tube will be clarified.

In summary, there are three main problems to be solved to improve the application of ALPs: (1) during the lifting process, the state changes of the flow inside the pump are unknown; (2) accurate formulas for the void fraction of each phase in the vertical pipeline of ALPs must first be derived to enable the calculation of other flow...
parameters; and (3) the relationship between the axial pressure distribution and the state of the flow process must be explored and verified.

This paper derives a formula for the void fraction of gas in the ALP system through experiments and establishes the GSE for steady flow in an ALP and an axial pressure distribution model. As ALPs can be used to lift both water and solids, the gas–liquid–solid three-phase flow can be treated as a gas–slurry two-phase flow. This paper analyzes the working mechanism and flow process in ALP lifting liquid. Air and water are used as representative gas and liquid, respectively; hence, unless otherwise stated, the gas–liquid flow in this paper refers to air and water. This work provides comprehensive experimental data and correlations to enable further investigations of ALPs.

The remainder of this paper is organized as follows. The GSE of ALP and the axial pressure distribution model are established based on the van der Waals formula in Sec. II. In Sec. III, a semi-empirical/semi-theoretical formula for the gas void fraction in an ALP system is derived from experimental data obtained using an electrical resistance tomography (ERT) system. The experimental design and results are described in Sec. IV. Finally, the conclusions to this study are summarized in Sec. V.

II. GSE AND AXIAL PRESSURE DISTRIBUTION MODEL OF ALP

ALP is considered to be an isothermal expansion engine driving a fluid/slurry. The configuration of ALP, shown in Fig. 1, is composed of a pipe inserted vertically into a water tank or silo. Near its bottom (I), air is injected, so that the tube is divided into two parts, i.e., below this point is the suction part, above is the suction part. The cross section of the pipe is uniform in area. Water/slurry is sucked in from the pipe inlet (E), and the air–water mixture is discharged from the pipe outlet (O). ALP has a simple structure and is essentially a tube with some holes through which air is injected. During the development of the pumping action, water and air are lifted by the consequent density difference and the water pressure induced by the vacuum formed by the rise in the air bubbles. The research reported in this paper is based on the following assumptions:

1. The flow is regarded as one-dimensional upward flow;
2. The air–water two-phase flow is in stable state;
3. The pressure of each phase is the same;
4. The pressures at the horizontal cross section are equal;
5. The temperature change of the fluid is negligible.

A. GSE of ALP

Previous studies on ALPs have mainly focused on the phase interface change, slippage, and flow patterns. However, this does not provide a comprehensive picture of how ALP systems operate. The first two factors mainly concern the microscopic aspects of gas–liquid two-phase flow, and the phase interface is complex and unpredictable; the flow patterns are qualitative. The interface change, slippage, and flow patterns of the two-phase flow are only the result of changes in the state of the two-phase flow. Qualitative research tends to result in discontinuities when switching from one flow pattern to another, whereupon subjective judgments must be applied. Moreover, the determination of flow patterns ultimately depends on state parameters such as the flow rate and void fraction of the gas–liquid two-phase flow. Stenning and Martin theoretically and experimentally proved that the performance of an ALP is insensitive to changes in the slip ratio.

Although it is important to study the governing changes in the two-phase interface and the flow patterns, the phase interface is unpredictable at the microscopic level. Thus, efforts should focus on the state process (e.g., relationship between pressure and the specific volume of gas) of the system. For a pipeline riser ALP system with large length-diameter ratio, the gas–liquid two-phase flow in stable state is always supposed to be one-dimensional upward flow to facilitate the theoretical analysis, the numerical calculation, as well as study of system efficiency and performance, e.g., Kassab et al. Wang et al., Shimizu et al., Shimizu and Takagi, Liu and Yao, Stenning and Martin, and Rim et al. So that the emphasis is focused on the states in the inlet and outlet, which make it easier to characterize how the flow stability and performance are influenced by the boundary working conditions. This simplification can provide truly valuable insights into the system without unnecessary complexity and the confusing three-dimensional field in the analysis of the theoretical model. This approach is sufficient for assessing and optimizing the system operation of ALPs under stable conditions. Hence, the flow stability and efficiency are mainly attributable to the state of the flow at the inlet and outlet. The state of the multiphase flow is typically determined by the state of the gas. The flow of the gas in the tube can be regarded as isentropic, but density changes cannot be neglected because ALPs are isothermal expansion engines in which the density differences of compressed gas are the only power source. To analyze the state process of the ALP system and its flow characteristics, the GSE of ALP is developed in this section.

In the ALP system, the temperature change of fluid is negligible since all material and equipment are at room temperature; hence,
temperature $T$ is constant. As the compressed gas flows from the air inlet into the pipe and flows out from the outlet, the gas participates in the transportation process of the two-phase flow and experiences the axial pressure variation in the upriser pipeline. In the flow direction, the pressure drop mainly includes three parts, i.e., gravitational pressure drop, acceleration pressure drop, and frictional pressure drop. Among them, the gravitational pressure drop occupies the largest proportion. Therefore, the axis pressure can be simply assumed to linearly decrease in the upward flow direction as the water depth decreases. According to the gas state equation $P = \rho cRT$, and the hydrostatic pressure, $P = P_a + \rho_gh$, the density of gas decreases linearly as water depth $h$ increases (along the flow direction, pressure decreases) linearly, i.e., specific volume of gas increases linearly during its upward flow. From the analysis above, we assume that the specific volume of the gas increases linearly during its upward flow. Therefore, the specific volume of the gas at different heights can be expressed as a function of the specific volume of the gas at the inlet, the specific volume of the gas at the outlet, and the height (or water depth),

$$v^h_G = \frac{L_{io} - h}{L_{io}} v_{G,io}^h + \frac{h}{L_{io}} v_{G,oi}, \quad (1)$$

where $L_{io}$ is the distance from the air inlet to the pipe outlet (m); $v_{G,io}$ is the specific volume of air (m$^3$/kg); $h$ is the distance to the air inlet (m); and the superscript "in" represents the air inlet.

According to the van der Waals equation, the GSE of the ALP yields

$$\left( P + \frac{a}{(\frac{L_{io} - h}{L_{io}} v_{G,io} + \frac{h}{L_{io}} v_{G,oi})^2} \right) (v - b) = RT, \quad (2)$$

where $R$ is the gas constant [J/(K mol)]; $T$ is the temperature (K); and $a$ characterizes the intermolecular attraction of the compressed air in the tube. The presence of intermolecular attraction means that the pressure exerted by the gas molecules on the wall is less than that in the ideal gas state, and $a/v^2$ represents a correction for the pressure. The parameter $b$ is the co-volume of gas, which represents the volume of the molecule itself in the total volume of the gas. In the ALP system, air is compressed so that the co-volume is non-negligible. Hence, $b$ is subtracted in the GSE of ALP.

As the specific volume of the gas at the outlet is known to be that at atmospheric pressure, the above-mentioned equation establishes the relationship between the axial pressure, location $h$, and the specific volume of the gas at the air inlet. The coefficients $a$ and $b$ can then be determined from the experimental pressures at several locations within the tube. In this way, the GSE of the ALP, as well as the axial pressure model, is established.

### III. VOID FRACTION OF GAS IN ALP

In industrial applications of ALPs, the most formidable task is the prediction of the void fraction of gas in the flow direction under a given working condition. Once the void fraction of gas is known, other parameters can be deduced, e.g., void fraction of fluid, real velocity of gas, fluid flow rate, momentum of each phase, and axial pressure distribution. Hence, the flow process in the tube can be readily clarified.

### A. Correlations for the void fraction of gas

The prediction of the phase distribution in a given working condition is difficult because the slippage between the gas and the liquid phases is complicated and unpredictable. Given the lack of a basic theory on the flow mechanism, the majority of gas void fractions are calculated based on empirical correlations. There are basically four types of correlations for calculating the gas void fraction of gas–liquid two-phase flow in pipeline systems. The homogeneous correlation ($e_h$) is derived by simply assuming that there is no slippage between the gaseous and liquid phases, so that the gas–liquid two-phase flow is handled as a homogeneous flow. The slip ratio correlations can be expressed as Eq. (3),

$$e = \frac{1}{1 + S \left( \frac{1 - x}{x} \right) \left( \frac{\rho_g}{\rho_l} \right)^{0.8} \left( \frac{\mu_l}{\mu_g} \right)}, \quad (3)$$

$K_{e_h}$ correlations are products of a flow parameter $K$ and the homogeneous correlation $e_h$, where the parameter $K$ is defined as a function of different parameters according to different researchers at different working conditions, e.g., it can be expressed as a function of $\rho_g$, pressure ($P$), Froude number ($Fr$), and/or dryness fraction $x$. Drift flux correlations are expressed as functions of a distribution parameter and a drift velocity, which is defined as the difference between the velocity of the gas and the mixture. General void fraction correlations are claimed to be the most empirical in nature because physical principles are incorporated into the formulas as physical parameters.

Most correlations were developed for a particular flow pattern and are only suitable for certain working conditions. Primarily, they were developed for horizontal and inclined orientations in fluidized beds, steam power plants, and nuclear power stations. These applications are completely different from the upriser ALP system considered in this work in terms of design purpose, process control, and environment. Different from fluidized beds, the goal of the upriser ALP system is to inject gas into the tube so that the liquid can be lifted out of the tube through the action of water pressure during the rise in the mass gas, rather than to maintain a certain gas–liquid state that promotes mass and heat transfer and chemical reactions by controlling the interface area of the gas–liquid two-phase flow. Different from thermal power plants and nuclear power plants, the working principle of the upriser ALP is simple, and there are no high temperatures or high pressures and no heat transfer processes such as evaporation and condensation. Some formulas claim to be universal, but their universality has not been verified by experiments. Therefore, they should not be used to calculate the void fraction of gas–liquid two-phase flows in upriser ALPs without careful verification.

Overall, to further study the working mechanism of the ALP system and provide a solid theoretical foundation for engineering applications, there is an urgent need for measurement experiments of the gas void fraction in upriser ALPs. Experimental data would enable us to derive a correlation for predicting the void fraction of each phase along the flow direction under certain working conditions, which is the basis of system design and flow assurance of upriser ALPs. In this work,
ERT is used to measure the void fraction of gas in the lifting process of an ALP system.

B. ERT

ERT can date back to 1920s, when geophysical researchers determined the distribution of oil rocks based on the formation resistivity distribution, which was collected by inserting arrays of electrodes into the ground, applying an exciting current to one pair of electrodes, and measuring the voltage response at the other pairs of electrodes.\(^{29,30}\)

Since its appearance, ERT technology has been widely developed and applied in industrial inspection fields such as industrial process imaging technology.\(^{31}\) The ERT system mainly consists of four parts: sensor array, data acquisition and processing unit, image reconstruction system, and computer, as shown in Fig. 2. For details of the working principles of ERT, see Ref.\(^{31}\).

In this work, ERT system (Model P2+, Industrial Tomography System Ltd., Manchester, UK) is used to collect gas void fraction data. There are four ERT sensors employed in the experiments, and each sensor contains a cross section, which is perpendicular to the axial direction of the pipe, and has 16 electrodes uniformly arranged around the pipe. To balance the image accuracy and reconstruction time, the linear back-projection reconstruction algorithm is adopted. The data collection rate is 10 fps with an excitation signal frequency of 9.6 kHz. The electrodes are connected to the data acquisition system (DAS), which is connected to the PC by a USB 2.0 cable. The tomography parameters used in this work are listed in Table I.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time interval (ms)</td>
<td>20</td>
</tr>
<tr>
<td>Injection current (mA)</td>
<td>75</td>
</tr>
<tr>
<td>Frequency of DAS (Hz)</td>
<td>9500</td>
</tr>
<tr>
<td>Data collection rate (fps)</td>
<td>10</td>
</tr>
<tr>
<td>Maximum number of frames</td>
<td>1000</td>
</tr>
<tr>
<td>Frames per download</td>
<td>1000</td>
</tr>
<tr>
<td>Electrodes per cross section</td>
<td>16</td>
</tr>
<tr>
<td>Pixel of each cross section</td>
<td>316</td>
</tr>
<tr>
<td>Inversion algorithm</td>
<td>Linear back-projection</td>
</tr>
</tbody>
</table>

IV. ANALYTICAL AND EXPERIMENTAL RESULTS

A. Experimental apparatus

To verify the GSE and the axial pressure distribution model of ALP, experimental data of pressure and gas void fraction were collected during the lifting process and a calculation formula was established. The experimental ALP used in this study is illustrated in Fig. 3.

The main components of the system are an air compressor, pressure regulator, air inlet, water storage tank, silo, riser, gas-liquid separation tank, vortex gas flowmeter, ultrasonic water flowmeter, pressure sensor, ERT sensor, high-speed camera, and computer. The lifting tube is 3.245 m long and is made of multiple transparent acrylic tubes connected by flanges with an inner diameter of 0.05 m. The pipe is inserted into a silo, which is connected to the water storage tank by a feeding water pipe. By ensuring the liquid level of the water storage tank remains constant, the submergence ratio \((Sr = \frac{L_{wa}}{L_{wo}})\) is fixed during the operation of the ALP. At different depths of the pipeline, three air inlets (I1–I3), eight pressure sensors (P1–P8), and four ERT test sections (ERT1–ERT4) are installed to collect the state parameters of the flow (volume flow rate, pressure, and gas void fraction). The four ERT sensors are divided into two pairs, which are located at the bottom and top of the pipe. Each pair of sensors are relatively close to each other so that the tiny change of gas void fraction can be detected; the two pairs of sensors are relatively far from each other so that the maximum difference of gas void fraction during the expansion of the lifting process is collected for verification of the hypothesis of linear change of gas density and the proposed axis pressure distribution model. Taking the inlet E of the tube as the origin of the coordinate system, the upward direction serves as the forward direction of the z axis. The coordinates of the data collection points are listed in Table II. According to Catrawedarma et al.,\(^{23}\) greater uniformity of the initial size and distribution of bubbles produces a more efficient system. Hence, the air inlet used in this experiment was designed as shown in Fig. 4. There are 48 small holes of diameter 3 mm, forming three rows and 16 columns uniformly distributed around the pipe, so that the air enters the pipe evenly. To visualize the flow process, the pipe, air inlet, and silo used in the experiment were made from transparent plexiglass.

To ensure the reliability of the pressure, void fraction, and volume flow rate collected during the experiment, high-precision equipment was used. The parameter configurations are given in Table III.

During the experiment, compressed air flows from the air compressor through the pressure regulator, gas vortex flowmeter, and the air inlet in turn, before entering the vertical lifting pipe. The gas and liquid are mixed in the tube and rise to the separation tank. In the
1. Air compressor
2. Pressure regulator
3. Vortex flowmeter
4. Air inlet
5. Riser
6. Separation tank
7. Water collecting tank
8. Return pipe
9. Silo
10. Ultrasonic flowmeter
11. Water storage tank
12. Feeding water line
13. High speed camera
14. Pressure sensor
15. ERT sensor
16. Computer

The ultrasonic flowmeter is installed in the horizontal return pipe section between the storage tank and the silo.

**B. Experimental process and data acquisition**

The sampling frequencies of vortex gas flowmeter, ultrasonic liquid flowmeter, pressure sensor, and ERT sensor are 50, 50, 4096, and 10 Hz, respectively. During each experiment, when the air flow rate reaches some predetermined stable value, the flow rates of air and water, and the pressures, and void fractions of gas are collected synchronously over a collection time of 100 s. The flow rates of the air and water are averaged over the 100 s experiment time. A data acquisition...
card (NI: USB-6361) is used to collect the voltage signal (0–5 V) at a sampling frequency of 4096 Hz, which is converted into a pressure signal by the DAQexpress data acquisition software. As there are fluctuations in the pressure of two-phase flow, the pressure is taken as the mean of the 95% confidence interval of the pressure signals collected within 100 s at a fixed gas flow rate. To better understand the flow process, images of the gas–liquid two-phase flow are taken at z = 1.3 under different air flow rates by a high-speed camera (Revealer: S1315) with a frame rate of 5000 fps and a resolution of 1280 × 960 pixels.

Since there is no suitable experimental data of gas void fractions and axis pressures to be used to verify the models proposed for the pipeline riser system of ALP in this paper, we carry out two kinds of experiments to collect two datasets, i.e., data I and data II. Data I includes the air flow rates and water flow rates, pressures, and gas void fractions under five working conditions, including I1W1 (with 13 different air flow rates, ERT1–ERT4), I1W2 (with 11 different air flow rates, ERT1–ERT4), IIW3 (with 15 different air flow rates, ERT1–ERT3), I2W2 (with 15 different air flow rates, ERT3–ERT4), and I3W2 (with 12 different air flow rates, ERT3–ERT4). Altogether there are 66 groups of gas–liquid two-phase flow data (includes 195 data points of gas void fractions) in ALP, this dataset is divided into two parts. The first includes 105 points of gas void fractions from ERT1 and ERT3, which is used to approximate the parameters of the proposed gas void fraction model (6); the second includes 90 points from ERT2 and ERT4, which is used to verify the feasibility of the proposed model. Based on data I, the GSE and the axial pressure distribution model of the ALP system were established, and the relationships between the gas void fraction, air specific volume at the air inlet, and water depth were obtained. Data II includes 343 groups of gas–liquid two-phase flow data, including liquid flow rates, pressures of eight positions along the flow direction, from about 17.1% at ERT1 and ERT2 to more than 80% of the feasible range. This large range of gas void fractions indicates significant variations in bubble sizes and lengths, as well as a large number of flow patterns, as can be verified in Fig. 6.

When the gas flow rate is small [0.05 m/s, Fig. 7(a)], the PDFs of gas void fractions at all four cross sections exhibit tall thin peaks on the left and long tails on the right. The average void fraction increases along the flow direction, from about 17.1% at ERT1 and ERT2 to 19.0% at ERT3 and ERT4. The most frequent gas void fractions are 6.2% and 8.4% for ERT1–ERT2 and ERT3–ERT4, respectively. The average void fractions are larger than the void fractions with the highest probability of occurrence. This shows that the gas in the tube normally rises in the form of bubble groups with small void fractions [Fig. 6(a)]; occasionally, bubbles with larger particle sizes appear, causing a sudden increase in the void fraction so that the PDFs have long tails on the right [Figs. 6(a) and 7(a)]. Although the gas flow rate is very small (too small to lift the water), the distribution of the gas void fraction in the tube is very wide, ranging from 0% to 85%. As the gas

### Table III. Ranges and accuracies of the experimental devices.

<table>
<thead>
<tr>
<th>Device</th>
<th>Range</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air compressor</td>
<td>0–0.8 MPa</td>
<td>±2.5</td>
</tr>
<tr>
<td>Vortex gas flowmeter</td>
<td>0–500 L/min</td>
<td>±2.5</td>
</tr>
<tr>
<td>Ultrasonic water flowmeter</td>
<td>0–15 m³/h</td>
<td>±0.2</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>0–35 kPa</td>
<td>±0.02</td>
</tr>
</tbody>
</table>

1. Void fraction of gas in ALP

Figure 6 shows photographs of the gas–liquid two-phase flow taken under six different gas flow rates at z = 1.3 m. As can be seen from Fig. 6, the air rises in such a way that the bubbles coalesce and are crushed, before being recycled and the process repeats. The size and length of the bubbles increase with increasing air flow rate. We speculate that, in the ALP system, the difference between flow patterns is manifested in the size and length of the bubbles. When the gas flow rate is small, the images are clearer; at larger gas flow rates, the images become blurrier. This reflects the rapid expansion of the gas and the extrusion of the liquid when the gas flow rate is too large, which increases the turbulence intensity in the pipe.

1. Analytical and experimental results

Figure 5 shows the relationship between superficial gas velocity ($J_G$, m/s) and superficial liquid velocity ($J_L$, m/s) under working condition I1W2. Only the air volume flow rate at the air inlet can be collected by the vortex gas flowmeter. Hence, in the remainder of this paper, unless otherwise specified, the air (water) flow rate refers to that measured by the vortex gas flowmeter (ultrasonic water flowmeter) and is converted into the superficial velocity $J_G$ ($J_L$) in the tube for simplicity. As can be seen from Fig. 5, when the gas flow rate reaches 0.09 m/s, the liquid can be lifted out, i.e., $J_G = 0.09$ m/s is the critical gas flow rate for lifting the liquid under working condition I1W2.
flow rate gradually increases from 0.09 to 1.26 m/s [Figs. 7(b)–7(d)], in addition to the same phenomena as in Fig. 7(a) (higher gas void fraction closer to the liquid surface), the range of void fractions expands from 0%–88% to 0%–99%, and the PDFs shift from being concentrated to being dispersed, and transition from unimodal to multimodal. The void fractions with the maximum occurrence begin to exceed the average void fractions. The large ranges of gas void fraction reflect that the crushing of gas slugs occasionally happens, so that bubble flow (with small gas void fraction), slug flow (with large gas void fraction), annular flow (with large gas void fraction), and stirred flow alternately appear. The flow field in the tube is unstable, the size and length of the bubbles are different, the distribution range of the gas

FIG. 6. Photographs of air–water flow at different $J_G$. 
void fraction grows, and the PDFs change from concentrated to dispersed and uniform.

As the gas flow rate further increases [Figs. 7(e) and 7(f)], air comes to occupy most of the volume in the tube, and the PDFs switch from multimodal to unimodal. When $J_G = 3.37 \text{ m/s}$, the range extends from about 20%–98%, which implies that bubble flow with a small gas void fraction no longer exists at large gas flow rates. The fluid in the tube mainly appears in the form of circular flow and stirred flow. The crushing of gas slugs occasionally occurs, followed by stirred wake flow. As a result, the PDFs show a right-peak-left-tail distribution.

From Figs. 7(a)–7(f), we find that the air expands along the flow direction at any gas flow rate.

Figure 8(a) indicates that, with increasing gas flow rate, the gas void fractions collected at all four cross sections (ERT1–ERT4) increase, albeit at a decreasing rate. The expansion degree decreases with increasing gas flow rate. The expansion degree in the lower part is more obvious than in the upper part of the pipe [Fig. 8(b)]. Based on this, it can be predicted that, under a given gas flow rate at the air inlet, the gas void fraction increases along the flow direction, which results in an increased $J_G$ along the flow direction because the mass flow rate of gas is constant.

According to the variations in the void fraction with the gas flow rate, an empirical formula (4) for the gas void fraction with respect to the gas flow rate is established. Here, $J_{G,\text{in}}$ is the gas flow rate at the air inlet, $e_{G,z}$ is the gas void fraction at cross section $z$, and $A$, $B$, $C$, $D$, and $E$ are parameters. The experimental gas flow rates and gas void fractions at cross sections ERT1–ERT4, as collected by ERT system, are used to fit Eq. (4). The resulting parameters are listed in Table IV. As can be seen from Table IV, $A$, $B$, $C$, $D$, and $E$ in Eq. (4) vary with the location $z$, produce a good fit with Eq. (4). This implies that the void fraction of gas in the pipe is not only related to the gas flow rate, but also to factors such as the distance from the air inlet, or, water depth,

$$e_{G,z}(J_{G,\text{in}}) = A + B/J_{G,\text{in}} + CJ^D_{G,\text{in}} + E\sqrt{J_{G,\text{in}}}. \quad (4)$$

As can be seen from Fig. 8(b), under different gas flow rates, the gas void fraction increases linearly along the flow direction. Therefore, a linear equation for the gas void fraction along the flow direction (5) is established. The coefficients under different gas flow rates are obtained by fitting the experimental data and are listed in Table V.

$$e_{G,z}(J_{G,\text{in}}) = K(z - z_0) + L. \quad (5)$$

Here, $z_0$ is the coordinate of the air inlet, $L = e_{G,\text{in}}$ represents the void fraction of gas at the air inlet, and the slope $K$ represents the increment in the gas void fraction per unit height. According to the continuity equation, $K$ reflects the rate of change of the specific volume of gas along the flow direction, that is, the expansion coefficient.

Table VI presents the correlations between $J_{G,\text{in}}$ and $e_{G,\text{ERT},i}$, $i = 1, 2, 3, 4$ observed in the experiments. There is a strong linear relationship between the gas void fraction and the gas flow rate, especially the axial gas void fraction along the flow direction. Thus, in the ALP system, the void fraction of gas in the pipe is affected by two factors: the air flow rate at the air inlet and the distance to the air inlet (or water depth). Obviously, the former can be regarded as an external factor, i.e., the amount of gas injected into the system from outside; the
latter is internal, i.e., an increase in volume due to the expansion of the gas as its density decreases in the flow direction. From the $K/L$ values in Table V, the gas void fraction increases by about 5%–11% of the volume at the air inlet per unit height under the working condition in the experiments. Therefore, in the ALP system, the expansion of gas along the flow direction cannot be ignored, especially for vertical pipeline transportation systems over long distances, such as in deep-sea mining.

In the ALP system, only the air flow rate at the air inlet can be controlled, the expansion process of the gas and the liquid flow rate are determined by the air coming in from the air inlet. Hence, it is necessary to predict the void fraction of gas at different heights under different air flow rates. From the above, the relationship of gas void fraction with water depth can be regarded as linear. According to power series expansion theorem, any smooth functions can be expressed as power series. Therefore, based on Eqs. (4) and (5) and the analysis above, the relationship between the gas void fraction, the gas flow rate, and the water depth is established as follows:

$$e_G = A + BJ_G;_{in} + CJ_G;_{in}^2 + DJ_G;_{in}^3 + EJ_G;_{in}^4 + Kz.$$  

(6)

Considering that the gas flows from the air inlet to the water surface, the location $z$ is normalized by $z' = (z_W - z)/(z_W - z_l)$ (normalized water depth), and here, $z_W$, $z_l$ are the coordinates of water surface and air inlet. In the model of gas void fraction defined by Eq. (6), the air flow rate is taken as the superficial velocity, and the water depth $z'$ is defined as the ratio of the water depth of point $z$ to the distance between water surface and air inlet. Therefore, model (6) describes the relationship between the gas void fraction and water depth and air flow rate at the air inlet, which can be used to predict the gas void fraction at any height of the ALPs with different lengths of pipe and different locations of air inlet.

The parameters of model (6) fitted by 105 data points of data I are shown in Table VII. The parameter $K$ represents the volume expansion rate of the gas along the flow direction. Since the normalized water depth is used in model (6) instead of distance from the air inlet,
$K$ is negative. In order to verify the model (6) developed, model (6) is used to predict the other 90 data points in data I, and the effectiveness of the proposed model is compared with those of 10 correlations from four types, which are considered to be most suitable for calculating the gas void fraction in gas-liquid two-phase flows in vertical uprisers, including $K_{TH}$ correlations proposed by Guzhev et al.,32 Greshov and Cooper,33 slip ratio correlations proposed by Lockhart and Martinelli,34 drift flux correlations proposed by Zuber and Findlay,35 Ishii,35 Steiner,36 Hibiki and Tsukamoto,37 and general correlations proposed by Sterman,38 Chisholm,39 Gomez et al.,40 see Fig. 9. It can be seen from Fig. 9 that model (6) fits the experiments best, and the relative error is basically in the range of 20%. The gas void fraction predicted by the model proposed contains two curves with the change of $J_G$, which corresponds to the positions of ERT1–ERT2 and ERT3–ERT4 where the gas void fractions are collected in the experiments. Other correlations fail to detect the developing trend of the gas void fraction with both the gas flow rate and the water depth. From Fig. 10, it can be seen that the root mean square error (RMSE)41 and the mean absolute percentage error (MAPE)41 of the proposed model are the smallest. The drift flux correlation proposed by Steiner36 plays second from the perspective of RMSE and MAPE. However, when the water flow rate is zero, the gas void fraction is ill predicted. This phenomenon happens in the slip ratio correlation (Lockhart and Martinelli34) and general correlation (Chisholm39), refer to Figs. S1–S10 in the supplementary material. This is because, when the air flow rate is too small to pump water, the dryness $x$ is equal to 1 because $J_L = 0$. Thus, the void fraction of gas converges to 1 at small flow rates [as calculated by Eq. (3)], which is far from the truth. The fundamental reason is that most of the correlations in the literature are derived from fluidized beds, thermal, and nuclear power plants, and so on, which are completely different from the ALP systems for lifting fluid/slurry. Although this does not happen for other correlations, however, the developing trends predicted are far from those in the experiments. As a result, there is an urgent need to develop a correlation for the gas void fraction in upriser ALP systems.

2. Pressure and specific volume of gas

Figure 11 compares the hydrostatic pressure with the pressures measured at eight different altitudes along the flow direction at 11 air flow rates. Under any gas flow rate, except around the air inlet, the axial pressure basically decreases linearly along the flow direction. The rate of decrease slows as the gas flow rate increases. The main reason is that, with an increase in the air flow rate, the average density of the gas-liquid two-phase mixture in the pipe decreases. At the air inlet, a larger gas flow rate creates a greater reduction in pressure. When the gas flow rate exceeds 0.42 m/s, the pressure decrease is obvious. When the gas flow rate is greater than 0.8 m/s, the pressure drops sharply, probably because the entrance of a large amount of gas results in an instantaneous accelerated pressure drop that cannot be ignored, producing a sudden drop of pressure near the inlet. Away from the air inlet, the pressure gradually reverts to a linear declination.

### Table VII. Parameters of Eq. (6) fitted using experimental data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$K$</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
<th>$E$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.0964</td>
<td>0.2258</td>
<td>0.5654</td>
<td>-0.1927</td>
<td>0.0025</td>
<td>0.0085</td>
<td>-0.0010</td>
</tr>
</tbody>
</table>

Figure 9. (a) Relationship of gas void fractions and gas flow rates in the experiments and those predicted by other 10 empirical correlations and (b) comparison of the gas void fractions predicted by 10 empirical correlations and the experiments.

Figure 10. RMSE and MAPE of the gas void fractions predicted by 10 empirical correlations and the model proposed in this work.
Fitting the GSE of the ALP [Eq. (2)] proposed in Sec. II A with the eight pressure values measured at P1–P8, we obtain the GSE for a given gas flow rate. As there are 11 different gas flow rates, we derive 11 GSEs from our experiments. The parameters of these GSEs are listed in Table VIII.

Figure 12 compares the pressures measured in the experiments with those predicted by the GSEs. The 11 lines correspond to the 11 GSEs described in Table VIII. The various discrete points represent the pressures measured during the experiments; each symbol includes eight points, representing the pressures at P1–P8 measured under the same gas flow rate. The large discrete points correspond to the same gas flow rate as lines with the same small symbol. Obviously, when the gas flow rate is small (less than 0.42 m/s), the pressure values calculated by Eq. (2) are in complete agreement with the experimental values; when the air flow rate is large (greater than 0.42 m/s), the pressure values calculated by Eq. (2) are basically consistent with the experiments, except for those near the air inlet. This reveals that, in the ALP system, except around the air inlet and at large air flow rates, the change in gas pressure in the upriser can be regarded as a quasi-equilibrium process and satisfies GSE (2), the parameters of which vary with the gas flow rate.

The underlying reason is that, in the ALP system, although the interface of the gas–liquid two-phase flow changes rapidly and unpredictably, the compressibility of air and the deformation ability of air and water mean that the air deforms and expands against the water with changes in the pressure field during the upward flow. This process (0–10 m/s) is relatively slow compared with the speed at which air molecules move. Hence, the state change of gas in the upriser ALP can be regarded as a quasi-equilibrium process and adheres to GSE (2) for the ALP system.

Table VIII demonstrates that the parameters of Eq. (2) are different under different gas flow rates. Parameter \(a\) first increases and then decreases with increasing gas flow rate. The threshold value \(J_G = 0.09\) m/s is the critical value at which water can be lifted out. When the gas flow rate is less than this threshold value, the gas volume in the pipe increases with increasing gas flow rate, but no water is discharged, so the gas–liquid two-phase flow above the liquid level fluctuates under the outlet, and the gradually increasing gas content is wrapped by water. As the gas density increases, the distance between air molecules becomes smaller, and the attraction \(a\) between the molecules becomes stronger. When the gas flow rate is greater than the critical value, the water can be lifted and discharged outside the tube. The internal kinetic energy and internal potential energy of the gas are transformed into those of the liquid. With the water being lifted and discharged outside the tube, the gas breaks free from the liquid and drains into the atmosphere, and the gravitational attraction between gas molecules reaches its maximum. Therefore, once the gas flow rate exceeds the critical value, the attraction between gas molecules is maximized and begins to decline as the gas flow rate continues to increase.

By comparing the GSEs of the ALP system under 11 different air flow rates with the ideal GSE (Fig. 13), it can be seen that the \(P-v\) curves for ALP are on the left-hand side of the ideal GSEs, and the ideal GSEs under different air flow rates overlap. When the gas flow...
rate is very small or very large, the GSEs for the ALP are close to the ideal GSE. By observing Table VIII, Figs. 13(b) and 14, it can be seen that the left and right distributions of the $P-v$ curves of the GSEs for the ALP correspond to parameter $a (a/v^2)$. A larger value of $a (a/v^2)$ shifts the $P-v$ curve to the left. As the gas flow rate increases, the GSEs of the ALP basically move to the right and do not cross the ideal GSEs.

Overall, the gas in the ALP cannot be regarded as ideal because the ideal GSEs cannot distinguish between different gas flow rates. However, the gas flow rate is the most important factor affecting the efficiency and capability of the ALP. Thus, using the ideal GSE to estimate the state of the system will introduce significant errors to the system design.

### 3. Efficiency of ALP

An ALP is like an isothermal expansion engine driving the movement of fluid/slurry. Therefore, the efficiency of the ALP is defined as the ratio of the net work done in lifting the liquid and the work done by the isothermal expansion of the air [Eq. (7)].

Many researchers have declared that the efficiency of ALPs is lower compared with that of other pumps. However, while this may be true for ALPs with low submergence ratios, in fields such as deep-sea mining, where the submergence ratio is close to 100%, the efficiency is amazing. As reported by Reinemann et al., ALPs can reduce energy losses by up to 60% compared with centrifugal pumps.

$$\eta = \frac{\rho_1 g Q_2 L_{WO}}{P_{in} Q_1 \ln(P_{in}/P_0)}.$$  (7)

As can be seen from Fig. 15, the efficiency first increases with $J_G$ to around 0.24 m/s and then decreases with further increases in $J_G$. This variation trend is similar to that of parameter $a$ in the GSE for ALP systems. This is reasonable because, in ALP systems, air is the only power source, and its state change during the lifting process can be seen as a quasi-equilibrium process in which the parameters $a$ and $b$ uniquely determine the state process and determine the work done by the expansion of gas. From this point of view, the working mechanism of ALPs...
can be attributed to the GSE for two reasons. First, in ALP systems, air is both the only power source and the working fluid that flows in accordance with the inner pressure field. Second, as the state change of the gas in the lifting process can be treated as a quasi-equilibrium process, the state of the ALP can be fully attributed to the GSE.

4. Validation of the proposed model

We have demonstrated that variations in the quantity and state of air within the ALP system obey a quasi-equilibrium process. Thus, during the process of the airlift pumping, the axial pressure distribution inside the tube can be predicted by the state process of the air. To verify the model proposed in this paper, the pressures collected by eight pressure sensors are used to fit the GSE of the ALP under a fixed air flow rate. The resulting GSE reflects the flow process inside the pipe under the fixed air flow rate, so that the axial pressure distribution can be predicted by the GSE.

When air is injected from I1 (I2, I3), there is no air below P1 (P3, P5) in the pipe, so the pressures at P1–P8 (P3–P8, P5–P8) are used to fit the GSE of the ALP. Figure 16 shows the axial pressure distributions predicted by the GSEs at different gas flow rates under the working conditions of I1W3. The various discrete points represent the experimental pressures. The different lines represent the pressures predicted by the GSEs, the gas flow rates of which correspond to the colors of the discrete identification points. Under different gas flow rates, the axial pressure distributions predicted by the GSEs agree well with the experimental values. Figures S11–S18 in the supplementary material indicate that, under all nine working conditions, the axial pressure distributions predicted by the GSEs are in reasonable agreement with the experimental data.

Figure 17 shows the eight pressure measurements collected at different gas flow rates under working condition I1W2. The pairs of identical symbols represent the 95% confidence interval of the pressure at a certain position and a certain gas flow rate. All eight pressures initially increase with increasing gas flow rate; once the gas flow rate exceeds 0.09 m/s, all eight pressures decrease with rising gas flow rate. In the experiments, \( J_G = 0.09 \text{ m/s} \) was found to be the critical gas flow rate for lifting the liquid. The reason for this phenomenon is the same as in Fig. 12, where \( J_G = 0.12 \text{ m/s} \) gives the critical value of \( a \) for lifting the liquid. When the gas flow rate is below the threshold value, no water is discharged as the gas flow rate increases, and increasing quantities of gas and water are accumulated under the outlet. Hence, the water surface in the upriser exceeds that in the water storage tank, and the pressure increases. When the gas flow rate is greater than the critical value, the water is lifted and the mixture is continuously and steadily discharged out of the tube. As the inner tube and the outer tube are connected by the gas–liquid flow, the pressure reaches a peak and begins to decrease as the gas flow rate increases. The phenomena in Figs. 14 and 17 are in accordance with the critical value \( J_G = 0.24 \text{ m/s} \) in Fig. 15, except for some slight hysteresis.
Figure 18 compares the pressures (P1–P8) measured in the experiments with those predicted by the ideal GSEs and the GSEs of the ALP system at different gas flow rates. Obviously, the pressures predicted by the GSEs of the ALP system agree well with the experimental results at P3, P4, and P7. The GSEs of the ALP system succeed in predicting the trend of the axial pressure distributions at all $J_G$, especially for the critical value of lifting water, which is in accordance with the trend in Fig. 17. In all cases, the pressures first increase with increasing gas flow rate. As the gas flow rate reaches the critical value, the pressures decrease with increasing gas flow rate. This phenomenon is more obvious at larger values of $z$ (i.e., closer to the water surface). However, the pressures calculated by the ideal GSEs fail to predict the critical value of $J_G$ for lifting water, while the pressures predicted by the ideal GSEs display the same trend for different gas flow rates. This again verifies that the ideal GSE fails to distinguish the effect of different gas flow rates on the ALP system.

Figure 19 shows the axial pressures distribution at different gas flow rates predicted by the ideal GSEs and the ALP GSEs. The discrete asterisks indicate the experimentally measured pressures. The axial pressures predicted by the GSEs of the ALP system are consistently more accurate than those predicted by the ideal GSEs. The goodness of fit of the ALP GSEs is in accordance with the order of the parameter $a$ in Fig. 14 (or Table VIII) and the efficiency in Fig. 15, which implies that the axial pressure distribution is a true reflection of the gas state process in the ALP.

V. CONCLUSIONS

This paper has investigated the GSE and axial pressure distribution of an ALP. The relationship between the axial pressure distribution and the axial specific volume distribution of gas was characterized by the GSE of the ALP system. High-precision pressure sensors, a commercial resistance tomography system, and high-speed camera were used to collect axial pressure measurements, axial gas void...
fractions, and flow visualization photographs of the air–water two-phase flow. The experimental data from three air inlets and three water depths were used to verify the effectiveness of the proposed model. The results show that the proposed model is in good agreement with the experiments and succeeds in predicting the states of the flow process in ALP. The following conclusions have been obtained:

(1) In the ALP system, under any gas flow rate, the PDFs of the gas void fractions do not stabilize near a single value, but are distributed over a relatively large range that occupies more than 80% of the feasible range. This large range of gas void fractions indicates widely differing bubble sizes and lengths, as well as a large number of flow patterns.

(2) In the ALP system, the gas expands along the flow direction, so the gas void fraction is a function of the gas flow rate at the air inlet and the distance to the air inlet. The gas void fraction increases by about 5%–11% of the volume at the air inlet per unit height. The density change of gas in the ALP cannot be neglected, especially for vertical pipeline transportation systems over long distances, such as in deep-sea mining.

(3) The gas flow rate is the most important factor in determining the stability, capability, and efficiency of the ALP system. However, the ideal GSE cannot distinguish the effect of the gas flow rate on the ALP, because the gas in the airlift pump cannot be regarded as ideal.

(4) The working mechanism and efficiency model of ALP systems can be attributed to the GSE of the ALP for two reasons. First, in ALP systems, air is both the only power source and the working fluid that flows in accordance with the inner pressure field. Second, as the changes in the gas during the lifting process can be treated as a quasi-equilibrium state, the axial pressure distribution and axial density distribution of the gas in the ALP system can be fully reflected by the GSE.

(5) The GSE for the ALP system was derived based on the measured pressures at several different heights under given working conditions. Different gas flow rates correspond to different GSEs. The parameter $a$ in the GSE reflects the gas flow rate, axial pressure distribution, and state process of ALP.

(6) The experimental data provide comprehensive and precise references for the design of ALPs. The proposed model provides a new methodology for studying the working mechanism and efficiency model of ALP systems and can be extended to long-distance transportation of slurries, fluids other than water, and solid, with constant or changing temperature fields, e.g., the upwelling of nutrient-rich deep-sea water and deep-sea mud, deep-sea mining, and so on. These are in the plan of our future studies.

**SUPPLEMENTARY MATERIAL**

See the supplementary material for details of the comparison between 10 correlations, the model proposed in this work, and the experiment, as well as the validation of the proposed model.

**ACKNOWLEDGMENTS**

This work is supported by the Hainan Provincial Key Science and Technology Program, Project No. ZDKJ 2021027; the Key...
AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Yanlian Du: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Writing – original draft (equal).
Jingyu Zhu: Investigation (equal); Validation (equal).
Xuanhe Han: Visualization (equal).
Mengdi Fu: Investigation (equal); Software (equal).
Yijun Shen: Funding acquisition (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

39 D. Chisholm, Two Phase Flow in Pipelines and Heat Exchangers (George Godwin in Association with the Institution of Chemical Engineers, London, 1983).