**Introduction**

The amount of water available for irrigation is lacking in Chinese remote mountainous regions because river water flows at the foot of the mountains, while the large areas of farmland are located on the hillslope. In addition, scattered villages and the unstable voltage of the power grid across the region sharply increase the total cost of delivering water to villagers via traditional pumping. Making full use of the water at the foot of the mountains is an urgent issue related to the livelihood of these villagers. To utilize the hydropower of the low water-head river, the appropriate design of energy conversion equipment is essential.

Considerable research efforts have sought to utilize low water-head hydropower rather than traditional energy sources such as oil, natural gas, and coal. Mankbadi and Mikhail [1] proposed a turbine-pump system, installed across irrigation structures, to drive a turbine connected to a pump to lift water for irrigation or domestic purposes. Francois et al. [2] invented a new type of turbine utilizing a microhydropower system with a simplified design.

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**Gas-water energy conversion efficiency in two-phase vertical downflow**

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**Abstract**

An automatic pump is developed using low water-head hydropower. The energy conversion efficiency $\eta$ of the gas-water energy conversion equipment is the focus. In this equipment, low-head water normally drains to the vertical downcomer. When water particles separate via gravity, a vacuum is generated, and air is mixed into the water spontaneously. High-pressure gas is ultimately produced at the end of the pipe. To discuss the effects of the air intake pipe diameter, river drop and water flow rate on $\eta$, a full-scale experiment is conducted, and an analytical solution based on the separation of water particles is derived. The air intake pipe diameter has almost no effect on $\eta$, but $\eta$ changes dramatically as the water flow rate varies. Meanwhile, $\eta$ initially increases and then decreases as the river drop increases. These findings enable the development of a method for low water-head hydropower utilization.
structure and higher performance. Date et al. [3] investigated a simple reaction water turbine for power generation from low-head microhydro resources. Parygin et al. [4] developed a criterion for comparing the efficiencies of various designs for siphon microhydroelectric power plants. These researchers planned to use a turbine to produce energy from low water-head hydropower, which still requires significant manpower and maintenance costs. Our research team is developing an automatic pump that utilizes low water-head hydropower. The low water-head hydropower project can pump water up to tens or hundreds of metres high using a river drop of 2–10 m and does not require any management. The low water-head hydropower project (Fig. 1) consists of two parts: gas-water energy conversion equipment and high-pressure pumps. The first part turns natural air into high-pressure gas by utilizing a river drop; the second part pumps water up to hundreds of metres high by utilizing the high-pressure gas. Once these devices have been deployed, they can be used to provide irrigation and domestic drinking water to villagers residing in remote parts of China.

High-pressure pumps have received considerable attention from many researchers [2, 5–10] over the last three decades. The gas-water energy conversion equipment is the focus of this research. In this type of equipment, low-head water normally drains to the vertical downcomer via gravity. When the water particles separate from each other, negative pressure is generated. Air is drawn into the vertical downflow pipe due to this negative pressure. After falling a considerable distance down the vertical pipe, the mass of air is subjected to higher pressures from the two-phase flow column above it, resulting in useful high-pressure gas being generated at the end of the pipe. Kuang et al. [11] showed that a significant vacuum can be generated in the vadose zone of the column when a finer layer exists at the top. The vacuum increases quickly in the earlier stage of the drainage, reaches a maximum, and then gradually dissipates. In addition, a number of researchers, such as Lucke and Beecham [12], Lucke and Arthur [13] and Beecham and Lucke [14], have discussed the phenomenon in which drainage systems develop annular flow at or slightly below atmospheric pressure in the downpipes, where as much as two-thirds of the pipe’s cross-sectional area is taken up by air. However, there is no scientific explanation regarding the generation of the vacuum. Our research explains why the vacuum occurs, namely, the separation of water particles by gravity.

For gas-liquid two-phase flow, the existing research objects are mainly vertical upflow, horizontal flow and inclined flow in pipes, while few papers have been published discussing the vertical downflow in large-diameter pipes. Oshinowo and Charles [15] established a similar but different form of classification for vertical downflows. Usui and Sato [16] investigated the void distribution and average void fraction in the three basic flow regimes: bubbly, slug, and annular flows. According to the results, profiles of the local void fraction in bubbly and slug flows show characteristic natures with a peak in the middle region between the center and the wall of the tube. The average void fraction for downward flow depends greatly on the flow regimes. Hibiki et al. [17] recommended a set of correlations applicable to the predictions of one-dimensional void fractions and interfacial area concentrations for a downward bubbly flow. Bhagwat and Ghajar [18] analyzed 1208 and 909 experimental data points for upflow and downflow, respectively, and demonstrated definite variations in the void fractions with varying phase flow rates. Many researchers [19–24] have investigated the flow patterns of the two-phase upflow and downflow. Most of these studies focused on small diameters less than 100 mm, with the exception of Almabrok et al. [24], who conducted an experimental study on gas-water flow behaviors in a vertical pipe with a diameter of 101.6 mm. Kaji and Azzopardi [25] investigated the effect of the pipe diameter on the flow characteristics of a two-phase flow. The pipes tested in this work have diameters of 160, 200, and 250 mm, which are considerably larger than those tested in previous studies. The flow pattern is different as a direct consequence of the change in pipe diameter. Therefore, research on the vertical downflow in large-diameter pipes is important.

![Figure 1. Aspects of the low water-head hydropower project.](image)
The gas-water energy conversion equipment is independent of the high-pressure pumps. In this article, we discuss the effects of several factors on the energy conversion efficiency $\eta$ of the gas-water energy conversion equipment. According to the gas-water energy conversion theory, we establish a homogeneous flow model to determine the effects of the factors on $\eta$. Basic theoretical research on gas-water energy conversion efficiency is still needed. By understanding the mechanisms of the interaction between air and water, we can optimize energy conversion efficiency, which is beneficial to the development of a method for low water-head hydropower utilization.

Experiments

Experimental setup

The full-scale experiment shown in Figures 2 and 3, with a test duration of approximately 1 year, was adopted. These tests were conducted at room temperature and...
atmospheric pressure between 0 and 30°C, regardless of the lab in which the measurements were taken. After the equipment was activated, water flowed into the vertical downcomer from the water intake tank, and air was mixed into the water spontaneously. The gas phase was compressed to generate high-pressure gas and was separated from the liquid phase in the gas-liquid separator, where the gas phase passed through the gas outlet pipe, while the liquid phase passed through the water outlet pipe. The height of the outlet pipe was consistent with the relative pressure of high-pressure gas of the isobaric surface analysis method (Fig. 4) such that the pressure of the high-pressure gas which is measured with the aid of a barometer can also be derived from the height of the outlet pipe. The value of the outlet pipe height is used only for rough comparison with barometer reading, and thus reduces the man-made error. A vortex shedding flowmeter installed at the end of the gas outlet pipe was used to measure the gas volumetric flow rate at room temperature and atmospheric pressure. We used another vortex shedding flowmeter to measure the liquid volumetric flow rate. Even if the two-phase flow had been separated once, the air in the water could not be separated completely, meaning that it may have affected the accuracy of the vortex shedding flowmeter for liquid. Therefore, by applying another separator, the residual air in the water was eliminated. Finally, all the water was gathered into a water storage tank for efficient water recycling. The formation mechanism of the high-pressure gas is described in detail in section 3.

The gas-liquid separator is made of ordinary steel to enable it to endure the unbalanced power resulting from the pressure differential. The respective parts of the equipment were designed to meet the conditions of the gas-liquid separator as shown in Table 1.

### Table 1. Materials of the gas-water energy conversion equipment.

| Equipment component | Material     | Unit size (mm) |
|----------------------|--------------|----------------|
| Water intake tank    | Fe360A       | 2000 x 800 x 500 |
| Air intake pipe      | PVC hard pipe | Φ25, Φ32, Φ40, Φ50, Φ75, Φ110 |
| Vertical downcomer   | PVC hard pipe | Φ160, Φ200, Φ250 |
| Gas-liquid separator | Fe360A       | Φ25, Φ32, Φ40, Φ50, Φ75, Φ110 |
| Gas outlet pipe      | PE corrugated pipe | Φ10 |
| Water outlet pipe    | PVC hard pipe | Φ400 |
| Water storage tank   | Fe360A       |                |
| Water recycle system | PE corrugated pipe |            |
The effects of different factors, such as $d_g$, $d_v$, $\Delta h$ and $Q_l$ on $\eta$ are studied in these tests. These tests are divided into 12 groups (Table 2). In each group, factors such as $d_g$, $\Delta h$, and $h'$ are the same, whereas factors such as $d_v$, $\delta$, and $Q_l$ are different. Options for $d_g$ have a certain randomness to restrict the test conditions of the PVC hard pipes that we used. $d_g$ was sorted out after completing all experiments and after comparing all test results rather than being planned ahead. Therefore, both the pump power (related to $Q_l$) and the air intake pipe should be varied for each group. As both change, we calculate $\eta$ according to equation (7).

In this study, we used a full-scale experiment and a series of factors to determine the impact on $\delta$. To keep costs low and reduce test durations, we used the multi-factor test method. The air intake pipe we tested is a single pipe with different diameters, that is, 25, 32, 40, 50, 75, and 110 mm. With the combined air intake pipes, we tested seven pipes with a diameter of 32 mm and 19 pipes with a diameter of 25 mm. The vertical downcomer tested is a pipe with different diameters, that is, 160, 200, and 250 mm. After applying the single air intake pipe and the combined air intake pipes, both $d_g$ and $\delta$ were analyzed simultaneously.

A preliminary test was conducted, which revealed that when the vertical downcomer is submerged, a liquid seal forms when $Q_l$ is between 80 and 210 m$^3$/h. These values of $Q_l$ can be achieved by adjusting the pump power.

In each test, we adjusted the pump power, causing $Q_l$ to change synchronously. However, if another factor is used as the variable, the pipe used in the tests must be changed each time to improve efficiency. Notably, $Q_l$ and the pump power have a nonlinear relationship, and $Q_l$ cannot be accurately controlled and increases nonlinearly in each test accordingly. We measured $Q_l$ using the vortex shedding flowmeter.

### Gas-Water Energy Conversion Theory

#### Process of forming high-pressure gas

We approach gas-water energy conversion theory as a two-phase flow problem. For the vertical downcomer, when the flow rate of water is large, the upside of the pipe forms a liquid seal. A schematic diagram of the experimental facility is shown in Figure 5.
To provide a more explicit description of the formation mechanism of the gas-water two-phase flow, the flow in the vertical downcomer is divided into two parts: the broken main flow and the filled flow. The broken main flow by definition dissipates due to gravity. The filled flow by definition is the rest flow to fill the void. Any part of the vertical downcomer, which has arbitrary length $\Delta l$, forms a long and narrow enclosed space. Within the enclosed space, the broken main flow, which has a flow rate and an initial flow velocity of $Q$ and $V_0$, respectively, has an acceleration $g$ and dissipates due to gravity. Both surfaces (the upper surface and the lower surface) of the main flow are filled with air or a gas-water mixture, which can be collectively referred to as filled flow, as previously stated.

Water particle movement in the horizontal pipe flow is different from that in the vertical pipe flow. In the horizontal pipe, all the water particles have the same flow velocity and no tendency to breakup, as there is no acceleration along the pipe line. However, in the vertical pipe, all the water particles are subjected to the force of gravity. Each unit of water at different locations in the vertical pipe has a different flow velocity. A lower pipe produces a higher flow velocity. The water bodies separate from each other, which increases with the flow distance. As the water bodies separate from each other, a negative pressure is generated. The filled flow tends to enter during the intervals of the broken main flow until a pressure balance between the two parts is reached.

The portion at the entrance of the variable diameter pipe is shown in Figure 5. Above this point is the gas phase, and below it is the gas-liquid phase (Fig. 5). In comparison, above and below other sections of the pipe, a gas-liquid phase exists. When the equipment is activated, a nonuniform stern flow is generated in the vertical downcomer. Interestingly, uniform two-phase flow forms in the vertical pipe as the flow falls. After dropping a long distance in the vertical pipe, the per unit air mass is subjected to greater pressures from the two-phase flow column above it, forming high-pressure gas at the end of the pipe.

**Expression for the energy conversion efficiency**

The energy conversion efficiency $\eta$ is the ratio of the usable energy output of the energy conversion equipment to the energy input. No consistent or well-accepted definition of the energy conversion efficiency $\eta$ between water
power and high-pressure gas power exists. The energy conversion efficiency \( \eta \) is mathematically defined as

\[
\eta = \frac{E_{\text{gas}}}{E_{\text{liquid}}}. \tag{2}
\]

The water power in equation (2) is given by

\[
E_{\text{liquid}} = mg \Delta h, \tag{3}
\]

where \( m \) is the mass of the low-head water and \( g \) is the local acceleration due to gravity.

The high-pressure gas power in equation (2) is given by

\[
E_{\text{gas}} = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{V_1 P_1}{V} dV = V_1 P_1 \ln \frac{P_1}{P_2}, \tag{4}
\]

where \( P_2 \) is the pressure at the trial sites, \( V_2 \) is the gas volume under the pressure at the trial sites, \( P_1 \) is the pressure of the high-pressure gas and \( V_1 \) is the volume of the high-pressure gas.

The low water-head hydropower, \( E_{\text{liquid}} \), is converted to high-pressure gas power, \( E_{\text{gas}} \). The high-pressure gas can do work when expanding at room temperature and atmospheric pressure until the pressure of this high-pressure gas gradually decreases to one bar of pressure.

Therefore, the energy conversion efficiency \( \eta \) is defined by

\[
\eta = \frac{V_1 P_1 \ln \frac{P_1}{P_2}}{mg \Delta h}. \tag{5}
\]

\[
V_1 P_1 = V_2 P_2 \tag{6}
\]

From equations (6) and (7),

\[
\eta = \frac{V_1 P_1 \ln \frac{P_1}{P_2}}{mg \Delta h} = \frac{V_2 P_2 \ln \frac{P_2}{P_1}}{mg \Delta h} \tag{7}
\]

By measuring \( Q_g \) and \( Q_l \) at atmospheric pressure, \( P_0 \) and \( \eta \) are calculated as

\[
\eta = \frac{E_{\text{gas}}}{E_{\text{liquid}}} = \frac{Q_g P_0 \ln \frac{P_0 + \Delta P}{P_0}}{Q_l \rho g \Delta h} \tag{7}
\]

where \( \rho_l \) is the density of the liquid phase.

Based on the formula structure analysis of equation (7), \( P_0 \), \( \rho_g \) and \( g \) are approximately constant, and \( \eta \) is a function of \( Q_g \), \( Q_l \), \( \Delta P \), and \( \Delta h \). The variables \( Q_g \), \( Q_l \), \( \Delta P \), and \( \Delta h \) are obtained via direct measurements, whereas \( \eta \) is calculated using equation (7). These factors are not independent, and interactions occur between them.

The variable \( Q_g \) is correlated with \( W_g \), \( d_\nu \), and \( \alpha \) by

\[
Q_g = W_g \frac{\pi d_\nu^2}{4} \alpha. \tag{8}
\]

The variable \( W_g \) has no significant linear correlation with \( W_l \), as different values of \( W_l \) arise from different values of \( S \). Gas in the vertical downcomer exchanges momentum with the water and is also affected by the buoyancy of water. The variable \( \alpha \) depends on the air viscosity, the surface tension of the water, the gas-liquid two-phase flow pattern, the diameter of pipes and the roughness of pipes, which results in a complex, multi-component and interactive process. The gas actual velocity \( W_g \) and the liquid actual velocity \( W_l \) are difficult to observe. Therefore, equation (8) is transformed into an approximation formula:

\[
Q_g = V_1 \frac{\pi d_\nu^2}{4} \beta. \tag{9}
\]

As a result, determining the effect of a series of factors on \( \eta \) is a complex and multi-factorial problem. The kinematic characteristics of the gas-liquid two-phase flow are far more complicated than those of a single-phase flow, meaning that significant errors will occur if a simple theoretical analysis is used. The flow pattern is different as a direct consequence of the change in the pipe diameter [25]. Therefore, a 1:1 scale model is employed in the test to avoid “distortions” associated with a scaled-down test. A large-diameter vertical downcomer is applied.

**Model of Homogeneous Flow**

**Basic assumption**

1. The two phases are well-mixed and distributed evenly.
   The model considers only the horizontal movement, that is, it ignores the vertical movement, and a one-dimensional movement model is established.
2. The two phases have the same actual velocity.
   \[
   W_g = W_l = V_1 \tag{10}
   \]
   \[
   \alpha = \beta \tag{11}
   \]
   \[
   S = 1 \tag{12}
   \]
3. Both the pressure at the bottom of the downcomer and the friction between the fluids and the pipe inner wall are neglected. The main flow is in free fall.
4. The gaps between the broken main flow are filled with air and water at a certain ratio.
5. The tendency of the main flow to flow backward is ignored.

6. The volume of the air phase remains the same from top to bottom in the vertical downcomer. Volume changes caused by compression are incorporated into the ratio of air to water.

**Derivation of analytical solutions**

The diameter of the vertical downcomer is \( d_v \), and the length of the vertical downcomer is \( L \). Therefore, the cross-sectional area \( A \) of the vertical downcomer is \( \frac{\pi d_v^2}{4} \).

The variable \( Q_m \) is the flow rate of the broken main flow. The flow of \( Q_m \) is determined by the gravitational acceleration \( g \) in the vertical direction, and the time required to reach the end, \( t_1 \), is defined as

\[
t_1 = \frac{Q_m}{A g} \tag{13}
\]

Next, the initial velocity \( V_1 \) is given by

\[
V_1 = \frac{Q_m}{A} \tag{14}
\]

During \( t_1 \), the water particles in the main flow fall a length \( l_1 \):

\[
l_1 = \frac{Q_m^2}{2A^2 g} \tag{15}
\]

If water with a flow rate \( Q_m \) is able to flow through a downcomer of diameter \( A \), the flow velocity must be more than \( V_1 \). However, in a partial downcomer with a length \( l_1 \), the actual speed of a water particle, \( V_1 \), is less than the ratio of \( Q_m \) to \( A \). This means that \( Q_m \) exceeds the capabilities of the downcomer and that the liquid phase submerges the downflow.

In addition, the separation of the main flow is very weak because of the zero initial velocity; hence, the gap between water particles is quickly filled by water. Apparently, no water particles separate from one another. Consequently, a liquid seal forms in this part of the downcomer. This part can be designed as a no-break section, whereas other parts can be designed as a break section.

The length of the break section is

\[
l_2 = L - \frac{Q_m^2}{2A^2 g} = L - \frac{V_1^2}{2g}. \tag{16}
\]

Water particles of the main flow \( t_2 \) are required to pass through this break section. In the break section, the force of gravity still exists, but the capabilities of the downcomer have no restrictions on water particle separation. The velocity of the water particles in this section is so large that gravitational acceleration leads to severe separation.

According to the basic assumptions, the length of the break section \( l_2 \) is a function of \( t_2 \):

\[
l_2 = V_1 t_2 + \frac{gt_2^2}{2}. \tag{17}
\]

From equation (17), we can derive an expression for \( t_2 \):

\[
t_2 = \frac{1}{g} \sqrt{\frac{V_1^2}{2} + 2gl_2 - \frac{1}{2}V_1} . \tag{18}
\]

By definition, from the volumetric principle method,

\[
\beta = \alpha = 1 - \frac{Q_m t_1 + A l_1}{A L}. \tag{19}
\]

Therefore, by rearranging equations (14) and (18), the gas volume flow fraction is

\[
\beta = \alpha = 1 - \frac{V_1 \left( \frac{1}{2} \sqrt{\frac{V_1^2}{2} + 2gl_2} - \frac{1}{2}V_1 \right) + l_1}{L} . \tag{20}
\]

Replacing the lengths of the no-break and break sections in equation (20) with equations (15) and (17), equation (20) becomes

\[
\beta = \alpha = 1 - \frac{V_1 \left( \frac{1}{2} \sqrt{2gL} - \frac{1}{2}V_1 \right) + l_1}{L} . \tag{21}
\]

In this equation, \( \beta \) and \( \alpha \) are functions of \( L \) and \( V_1 \):

\[
\beta = \beta (L, V_1). \tag{22}
\]
Model Comparisons to Laboratory Experiments

Experimental results for the flow pattern

Oshinowo and Charles [15] proposed a flow pattern map (Fig. 6) for two-phase gas-liquid vertical downflow. As shown in Figure 6, our experimental results indicate that the flow patterns in the vertical downcomer are bubbly slug flow and falling film flow, which are consistent with the naked-eye observations. Here, FrTp is the mixture Froude number, Λ is the property modifying group, and Rv is given by

\[ R_v = \frac{\beta}{1 - \beta} \]  (23)

Relationship between η and dg

Contours are applied to the original data and the interpolated data under various conditions, as shown in Figures 7–9. The values shown on the lines represent the energy conversion efficiency η. The x-axis represents the area ratio of the air intake δ related to dg, and the y-axis represents the liquid volumetric flow rate Ql.

As shown in Figures 7–9, the contour lines are parallel to the x-axis. The value of η changes dramatically with Qp, that is, Qp has a significant impact on η. However, determining if increasing Ql increases η requires further investigation. Furthermore, via the analysis, we see that η is nearly constant as δ changes. From this result, we conclude that not only δ but also dg (or δ) does not significantly affect β.

Based on the homogeneous model discussed above, the separation of water particles has nothing to do with the air intake pipe. Because β(L, V1) is a function of L and V1, dg (or δ) does not significantly affect β.

An expression for η was developed. For two-phase flow in a vertical downcomer, η is given as a function of β via approximation. Replacing the ratio of Qx to Ql in equation (7) with equation (24), the expression for η, equation (7), becomes equation (25):

\[ \text{Figure 7. Variation in the contours of } \eta \text{ with } \delta \text{ and } Q_l \text{ in the } \Phi 160 \text{ vertical downcomer.} \]
When only the air intake pipe is changed, $P_0$, $\Delta h$, and $\Delta P$ or even $\beta$ are constant; hence, $\eta$ is also constant. The model and conclusions are verified by the test results above—not only $\delta$ but also $d_g$ has almost no effect on $\eta$.

The scale of $\delta$ in this experiment is between 2.44% and 21.97%. Cheng et al. [26] found that the initial bubble size has strong effects on the flow pattern transition and the instabilities of void fraction waves. The critical void fraction required for a flow pattern transition to occur decreases as the bubble size increases. More work is needed to determine when $d_g$ of one pipe becomes either tiny ($<2.44\%$, at which point the initial bubble size is affected) or large ($>21.97\%$, at which point the initial liquid flow is affected).

**Figure 8.** Variation in the contours of $\eta$ with $\delta$ and $Q_l$ in the $\Phi$200 vertical downcomer.

\[
\frac{Q_g}{Q_l} = \frac{\beta}{1 - \beta}, \tag{24}
\]

\[
\eta = \frac{\beta}{1 - \beta} \frac{P_0 \ln \frac{P+\Delta P}{P_0}}{\rho g \Delta h}. \tag{25}
\]

Relationship between $\beta$ and $\Delta h$

Taking the first partial derivative of equation (22) with respect to $L$, we arrive at

\[
\frac{\partial \beta(L,V_i)}{\partial L} = V_i \frac{1}{2gL^2} \left( \sqrt{2Lg} - V_i \right) > 0. \tag{26}
\]

According to equation (26), $\beta$ increases with $L$, but the growth of $\beta$ has a slower trend. The mathematical relationship between $L$ and $\Delta h$ is

\[L = \Delta h + h'. \tag{27}\]

If the value of $h'$ in equation (27) is treated as a constant, then $\beta$ increases with $\Delta h$.

The experiment was designed according to Table 3. The relationship between $\Delta h$ and $\beta$ is shown in Figures 10 and 11. The light colors indicate a high $\beta$ value, and all the light colors have higher $\Delta h$ values, meaning that $\beta$ increases with $\Delta h$. The conclusion is similar to that obtained based on the prediction model.
Taking the second partial derivative of equation (22) with respect to $L$, we arrive at

$$\frac{\partial^2 \beta(L,V)}{\partial L^2} = V \frac{1}{gL^2} \left( V_1 - \frac{3}{4} \sqrt{2gL} \right) < 0. \quad (28)$$

According to equation (26), $\beta$ increases with $L$. This calculation shows that $\beta$ varies with $\Delta h$ logarithmically such that $\frac{1}{\beta}$ also logarithmically varies with $\Delta h$. A new variable is defined to express this change rule:

$$\zeta(\Delta h) = \frac{\beta(\Delta h)}{1 - \beta(\Delta h)}. \quad (29)$$

The curve of $\zeta(\Delta h)$ varies logarithmically with $\Delta h$. Therefore, its relationship with $\Delta h$ is

$$\begin{cases} d\zeta(\Delta h) > 1 & \Delta h < \Delta h_i \\ 0 < d\zeta(\Delta h) \leq 1 & \Delta h \geq \Delta h_i \end{cases} \quad (30)$$

When $\beta$ in equation (25) is changed to $\zeta$, equation (25) becomes

$$\eta = \zeta(\Delta h) \frac{P_1 \ln \frac{P_{1\Delta h}}{P_{1i\Delta h}}}{\rho g \Delta h} = \frac{\zeta(\Delta h) P_1 \ln \frac{P_{1\Delta h}}{P_{1i\Delta h}}}{\rho g} = C \frac{\zeta(\Delta h) \Delta h}{\Delta h} \quad (31)$$

In this equation, $C$ is constant. Therefore, when $\Delta h < \Delta h_i$, $\eta$ increases with $\Delta h$. In contrast, when $\Delta h \geq \Delta h_i$, $\eta$ decreases with $\Delta h$.

Table 3. Test schemes of relationship between $\Delta h$ and $\beta$.

| Condition no. | $d_v$ (mm) | $d'$ (mm) | $h'$ (m) |
|---------------|------------|-----------|----------|
| B1            | 110        | 110       | 5        |
| B2            | 110        | 250       | 5        |
| B3            | 160        | 400       | 5        |
| B4            | 160        | 400       | 5        |
| B5            | 200        | 400       | 6        |
| B6            | 200        | 400       | 5        |
| B7            | 250        | 400       | 5        |
| B8            | 250        | 400       | 6        |

Figure 9. Variation in the contours of $\eta$ with $\delta$ and $Q_l$ in the $\Phi 250$ vertical downcomer.
Figure 10. Variation in the contours of $\beta$ with $\Delta h$ and $Q_l$ in the $\Phi_{110}$ and $\Phi_{160}$ vertical downcomers.

Figure 11. Variation in the contours of $\beta$ with $\Delta h$ and $Q_l$ in the $\Phi_{200}$ and $\Phi_{250}$ vertical downcomers.
η decreases with Δh. The value of η initially increases and then decreases as Δh continues to increase.

The experiment was designed according to the data in Table 4. When Δh > 2 m, η decreases as Δh increases (Fig. 12). We note that these are preliminary findings and that more research is needed for cases when Δh < 2 m.

**Table 4. Test schemes of relationship between Δh and η.**

| Condition no. | d_v (mm) | d'_v (mm) | h'_v (m) |
|---------------|----------|-----------|----------|
| C1            | 160      | 400       | 5        |
| C2            | 160      | 400       | 6        |
| C3            | 200      | 400       | 6        |
| C4            | 200      | 400       | 5        |

In our homogeneous flow model, based on the assumptions that β = α and that the filled flow (Fig. 4) consists solely of air, the estimations of β are all >70%. In an actual vertical downcomer, the actual values of β are all <25%. Because S < 1 when buoyancy pushes the air up inside the vertical downcomer, β < α can be derived from equation (34). In addition, the filled flow actually consists of both air and water, which reduces the value of β considerably.

**Conclusions**

In this report, we describe an automatic pump developed to utilize low water-head hydropower. The energy conversion efficiency η of the gas-water energy conversion equipment is the focus of this work. Within this equipment, low-head water normally drains to the vertical downcomer. When the water particles separate from one another by
gravity, a vacuum is generated. The flow in the vertical downcomer is divided into two parts: the broken main flow and the filled flow. The filled flow generally tends to enter during the intervals of the broken main flow until a pressure balance between the two parts is reached. High-pressure gas is generated at the end of the pipe.

In this article, we discuss the effects of many factors on the energy conversion efficiency \( \eta \) of the gas-water energy conversion equipment. According to gas-water energy conversion theory, we establish a homogeneous flow model and derive an analytical solution based on water particle separation to determine the effects of different factors on \( \eta \), such as the air intake pipe diameter \( d_g \), river drop \( \Delta h \) and water flow rate \( Q_l \). According to the test results and the analytical solution, \( \eta \) changes dramatically as \( Q_l \) varies, but the effect of an increase in \( Q_l \) on \( \eta \) requires further investigation. Furthermore, we determine that \( \eta \) is nearly constant as \( \delta \) changes, meaning that both \( \delta \) and \( d_g \) have almost no effect on \( \eta \) as long as \( \delta \) is between 2.44% and 21.97%. More work is needed to determine the effects when the \( d_g \) of one pipe becomes either very small (<2.44, at which point the initial bubble size is affected) or very large (more than 21.97%, at which point the initial liquid flow is affected). The value of \( \beta \) increases with \( \Delta h \), but the increase in \( \beta \) exhibits a deceleration. In addition, \( \beta \) varies logarithmically with \( \Delta h \). When \( \Delta h < \Delta h_{\text{opt}} \), \( \eta \) increases with \( \Delta h \). In contrast, when \( \Delta h \geq \Delta h_{\text{opt}} \), \( \eta \) decreases with \( \Delta h \). The value of \( \eta \) initially increases before decreasing as \( \Delta h \) increases.

An analytical solution is developed from the assumption that \( \alpha = \beta \) and \( W_g = W_l \) in the homogeneous flow model. In contrast, the slip ratio \( S \) is taken into account in the separated flow model. Presently, no reliable method for calculating \( S \) exists. In our homogeneous flow model, based on the assumptions that \( \beta = \alpha \) and that the filled flow consists solely of air, the estimations for \( \beta \) are all >70%. In an actual vertical downcomer, the actual values of \( \beta \) are all <25%. Because \( S < 1 \) when buoyancy pushes air up into the vertical downcomer, \( \beta < \alpha \) can be derived. In addition, the filled flow actually consists of both air and water, which considerably decreases \( \beta \). The findings can optimize energy conversion efficiency, which is instrumental to the development of a method for low water-head hydropower utilization. This paper provides a qualitative discussion of the factors and a quantitative analysis of the homogeneous flow model, which are required for further research.

**Acknowledgments**

The research work described herein was funded by the National Natural Science Foundation of China (NSFC, Grant Numbers: 41672257) and by the Fundamental Research Funds for the Central Universities (Project Number: 2018B12914). It was also supported by the Opening Project of the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute (Project Number: 2016491611). Their financial support is gratefully acknowledged.

**Conflict of Interest**

None declared.

**Nomenclature**

- \( \eta \) energy conversion efficiency
- \( E_{\text{liquid}} \) water power
- \( E_{\text{gas}} \) high-pressure gas power
- \( Q_g \) gas volumetric flow rate
- \( Q_l \) liquid volumetric flow rate
- \( P_0 \) standard atmospheric pressure
- \( \Delta P \) relative pressure of high-pressure gas
- \( \Delta h \) river drops
- \( W_g \) gas actual velocity
- \( W_l \) liquid actual velocity
- \( V_g \) gas superficial velocity
- \( V_l \) liquid superficial velocity
- \( d_g \) diameter of vertical downcomer
- \( h' \) height of outlet pipe
- \( d' \) diameter of outlet pipe
- \( d_g \) diameter of air intake pipe
- \( \alpha \) void fraction
- \( \beta \) gas volume flow fraction
- \( S \) slip ratio
- \( \delta \) area ratio of air intake pipe

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