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Study on the Factors Influencing the Water Discharge Performance of a Straw Water Pump

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Abstract: *A straw water pump is a simple fluid transport device that utilizes centrifugal force to lift liquid, and its water output performance is influenced by multiple factors, including the geometric parameters of the straw, rotational speed, and immersion depth. Based on fluid mechanics theory, this paper establishes a theoretical analysis model for the straw water pump. The influence of depth on flow velocity is analyzed using the Bernoulli equation, while a force balance condition for stable flow is obtained through a mechanical analysis of a fluid microelement within the rotating straw. By combining this with the power balance relationship, a quantitative relationship between flow velocity and the straw diameter, rotational angular velocity, and immersion depth is derived. Theoretical analysis indicates that the water output per unit time increases with larger straw diameter and higher rotational angular velocity, while it exhibits a nonlinear characteristic of initially increasing and then stabilizing with greater immersion depth. This study provides a theoretical basis for the structural optimization and performance prediction of straw water pumps.*

Keywords: *Straw Water Pump, Centrifugal Force, Bernoulli Equation, Power Balance, Water Output*

1. Introduction

The straw water pump is a fluid lifting device with a simple structure and no need for an external power source. Its working principle is based on the synergistic effect of centrifugal force generated by rotation[1]and fluid pressure difference[2]. When one end of the straw is immersed in the liquid and the other end rotates with the rotating shaft, the liquid rises along the tube wall under the action of centrifugal force and flows out continuously, forming a continuous water pumping effect. This device has broad application prospects in small-scale water conservancy, experimental teaching, and daily scenarios.

The performance of the straw water pump is mainly reflected in the water output per unit time, which is influenced by multiple factors such as straw length, diameter, immersion depth, and rotational speed. Existing studies have mostly focused on numerical simulations of the hydraulic performance of centrifugal pumps[3], while theoretical model research on simple devices such as the straw water pump remains insufficient. This paper aims to establish a comprehensive theoretical analysis framework for the straw water pump. Starting from the fundamental equations of fluid mechanics[4], the quantitative relationships among the influencing factors are derived, the underlying physical mechanisms are revealed, and theoretical support is provided for subsequent optimization design.

2. Theoretical Basis and Model Establishment

2.1. Bernoulli Equation and the Influence of Depth

According to the Bernoulli equation[5], for steady flow of the fluid within the straw, neglecting viscous losses[6], the Bernoulli equation can be applied along a streamline:

$$p_1+\frac{1}{2}\rho {v_1}^2+\rho g h_1=p_2+\frac{1}{2}\rho {v_2}^2+\rho g h_2 \tag{1}$$

where p is the pressure, ρ is the fluid density, v is the flow velocity, g is the gravitational acceleration, and h is the height.

For the straw water pump, both ends are exposed to the atmosphere, so it can be approximately considered that $p_1 \approx p_2$, and equation (1) is simplified to:

$$\frac{1}{2}\rho({v_2}^2 - {v_1}^2) = pg(h_1 - h_2) \tag{2}$$

Let the depth difference of the straw immersion be denoted as $\Delta h = h_2 - h_1$. If the flow velocity at the straw inlet is small and negligible, the outlet flow velocity is approximately:

$$v_2 = \sqrt{2g\Delta h} \tag{3}$$

Equation (3) indicates that under ideal conditions, the outlet flow velocity is proportional to the square root of the immersion depth. However, in actual flow, factors such as viscous resistance[7], centrifugal force, and frictional losses along the pipe introduce more complex nonlinear characteristics to the influence of depth.

2.2. Force Analysis of Fluid Element in a Rotating Tube

To more accurately describe the flow under rotating conditions, a fluid element of length dl within the straw is considered for analysis. In the rotating reference frame, this fluid element is subjected to the following forces:

Centrifugal force: $dF_c = \rho\omega^2 rAdl$, directed radially outward;

Gravity: $dF_g = \rho gAdl$, directed vertically downward;

Pressure difference: $dF_p = \rho gAdl$, acting along the pipe axis;

Frictional force: $dF_f = \tau_w \pi d \mathrm{d}\Delta l$, opposite to the flow direction.

Establish the force balance equation along the pipe axis direction (which forms an angle θ with the horizontal):

$$dF_c \cos\theta = dF_f + dF_p + dF_g \sin\theta \tag{4}$$

When the upward component of the effective centrifugal force along the tube is greater than or equal to the sum of the resistances, the fluid can overcome gravity and friction to achieve continuous rising. The critical condition is defined as:

$$\rho\omega^2 \mathrm{RA}\Delta l \cos\theta \geq \tau_\omega \pi d\Delta l + A\Delta p + \rho gA\Delta l \sin\theta \tag{5}$$

where R is the average distance from the fluid element to the rotation axis. Equation (5) reveals the combined effects of rotational speed, tube diameter, and immersion depth on the initiation and maintenance of flow.

2.3. Power Balance and Relationship with Flow Velocity

To further quantify the relationship between flow velocity and various parameters, the power balance of the entire straw system is considered. Under steady-state flow, the power provided by centrifugal force should equal the sum of the power consumed in overcoming resistance, pressure, and gravity:

2.3.1. Centrifugal Force Power

$$P_c = P_f + P_p + P_g \tag{6}$$

The power done by centrifugal force on the fluid[8] is:

$$P_c = \rho\omega_2 RvA \cdot \Delta r \tag{7}$$

where Δr is the radial displacement of the fluid element, v is the flow velocity along the tube, and A is the cross-sectional area.

2.3.2. Frictional Force Power

When the fluid flows along the tube, the frictional loss is calculated using the Fanning equation[9]:

$$\Delta pf = \frac{2fL\rho v^2}{d} \tag{8}$$

Then the power of the frictional force is:

$$P_f = \Delta p_f \cdot Q = \frac{2fL\rho v^3 A}{d} \tag{9}$$

where the friction factor is related to the Reynolds number[10].

2.3.3. Pressure Power and Gravitational Power

The power generated by the static pressure difference is:

$$P_p = \Delta p \cdot Q = \rho g h \cdot vA \tag{10}$$

The power required to overcome gravity is:

$$P_g = pgvA\Delta h \tag{11}$$

2.3.4. Comprehensive Expression

Substituting equations (7), (9), (10), and (11) into equation (6) and rearranging yields:

$$\rho\omega^2 RvA\Delta r = \frac{2fL\rho v^3 A}{d} + \rho ghvA + \rho gvA\Delta h \tag{12}$$

Eliminating the common factor ρvA, we obtain:

$$\omega^2 R\Delta r = \frac{2fLv^2}{d} + g(h+\Delta h) \tag{13}$$

From this, the expression for the flow velocity v is solved:

$$v = \sqrt{\frac{d\left[\omega^2 R\Delta r - g\left(h+\Delta h\right)\right]}{2fL}} \tag{14}$$

Equation (14) is the theoretical expression for the outlet flow velocity of the straw water pump, revealing the influence of various parameters on the flow velocity.

3. Experimental Results and Data Analysis

The experiment adopted the control variable method to investigate the effects of straw depth, diameter, and rotational speed on water output, respectively.

3.1. Effect of Depth on Flow Velocity

With the straw diameter and rotational speed fixed, the immersion depth of the straw was varied, and the water output per unit time was measured. The results are shown in Table 1.

Table 1: Flow velocity data at different depths

Depth(cm)	2	4	6	8	10
Flow velocity(ml/s)	6.45	7.25	8.20	9.09	9.60

Based on the data in Table 1, plot Figure 1 showing the variation of flow velocity with depth.

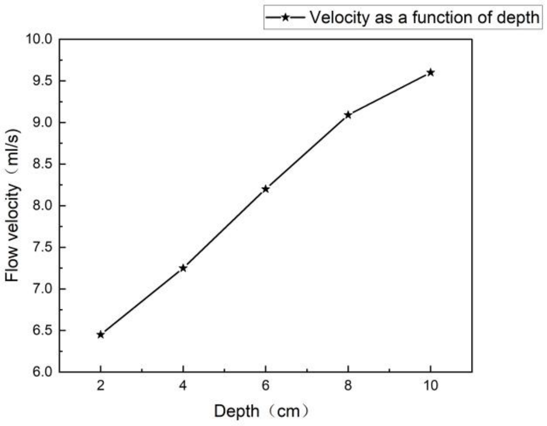

Figure 1: Line chart of flow velocity versus depth

The experimental results show that as the depth increases, the flow velocity gradually increases, but the rate of increase gradually slows down. Theoretical analysis indicates that when the depth exceeds a certain critical value, the effect of gravity becomes stronger, which may lead to a decrease in flow velocity. Although the inflection point of decline has not yet appeared within the range of this experiment, the observed trend is consistent with the theoretical prediction.

3.2. Effect of Diameter on Flow Velocity

With the straw depth and rotational speed fixed, straws of different diameters were used successively for testing. The results are shown in Table 2.

Table 2: Flow velocity data at different diameters

Diameter(cm)	1	2	3	4	5
Flow velocity(ml/s)	8.05	9.26	10.42	11.36	12.20

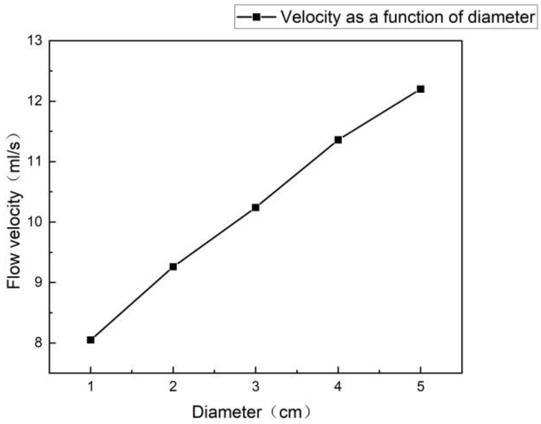

Figure 2: Line chart of flow velocity varying with straw diameter

From Figure 2, the experimental results show that the flow velocity increases significantly with the increase in straw diameter. The increase in diameter reduces the flow resistance, which is consistent with the prediction of the theoretical expression.

3.3. Effect of Rotational Speed on Flow Velocity

With the straw diameter and depth fixed, the rotational speed of the electric drill was gradually increased, and the water output per unit time was measured. The results are shown in Table 3.

Table 3: Flow velocity data at different rotational speeds

Rotational speed(rab/min)	50	100	150	200	250
Flow velocity(ml/s)	5.41	7.04	8.47	9.71	10.53

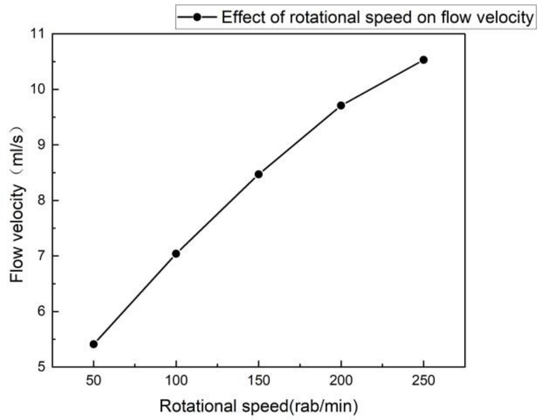

Figure 3: Line chart of flow velocity versus rotational speed

The experimental data in Figure 3 show that the flow velocity increases with rotational speed, and the rising trend is relatively stable. Rotational speed directly affects the magnitude of centrifugal force and is a key parameter controlling the outflow performance. This is fully consistent with the theoretical analysis that v increases with increasing ω.

4. Conclusions

Based on the fundamental theories of fluid mechanics, this paper establishes a comprehensive theoretical analysis model for the straw water pump. Through the Bernoulli equation, force analysis, and power balance, the quantitative relationships between flow velocity and parameters such as straw diameter, rotational angular velocity, and immersion depth are derived. The main theoretical conclusions are as follows:

(1) Effect of depth: The water output exhibits a nonlinear trend of initially increasing and then stabilizing with increasing immersion depth. An optimal depth range exists, beyond which gravitational resistance becomes dominant and may lead to a decrease in water output.

(2) Effect of diameter: The outlet flow velocity is proportional to the square root of the straw diameter. Increasing the diameter can effectively reduce flow resistance and improve water output.

(3) Effect of rotational speed: The flow velocity increases with increasing rotational angular velocity. Centrifugal force is the main driving force for the upward movement of the fluid.

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