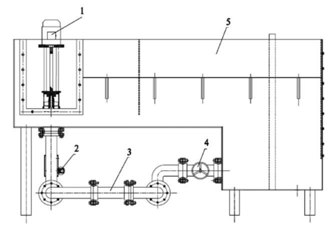
Analysis on the hydraulic and thrust characteristics of a miniature water-jet propulsion pump



Análisis sobre las características hidráulicas y de empuje de una bomba a propulsión por agua en miniatura

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RESUMEN

- Las bombas de propulsión por chorro de agua, generan una fuerza de acción por el flujo de agua en su salida en forma de salida libre, sin sufrir oposiciones resultantes de efectos contrarios de tuberías o válvulas y sus características de empuje están influidas por las características del flujo de agua. Se proponen en el estudio modelos de cálculo y ensayo de las características hidráulicas y de empuje para una mini-bomba de propulsión por chorro de agua para determinar las relaciones entre las características hidráulicas y el empuje de la bomba. El modelo para el cálculo hidráulico se establece mediante el método del coeficiente de velocidad y la predicción de empuje, mientras que el modelo para el ensayo en estado abierto se establece considerando las características de trabajo de la bomba. Se estudian: el coeficiente de presión a la salida de agua de la bomba de propulsión, la distribución de velocidad en la sección de salida, las características de empuje a diferentes velocidades de giro y las características dinámicas a diferentes distancias de la salida al fondo de la piscina, basándonos en la dinámica de fluidos y el teorema de cantidad de movimiento, verificando la precisión del modelo mediante el ensayo. Los resultados muestran que el caudal de la mini-bomba presenta una relación lineal respecto a la elevada velocidad de giro de la bomba y que la velocidad axial, en la zona cuando es menor que o igual a -1,5 m/s, tiene correlaciones positivas tanto con la velocidad de giro como con la distancia de la salida al fondo de la piscina. Los resultados indican también que el empuje de una mini-bomba de propulsión por chorro de agua está influido por la distancia del extremo al fondo: cuando la distancia es mayor que 0,8 m, la piscina de ensayo no influye en el empuje de la bomba. Los resultados de la investigación son muy significativos para establecer una base de ensayo de una mini-bomba de propulsión por chorro de agua y evaluar su rendimiento.
- **Palabras clave:** Bomba de propulsión por chorro de agua / bomba eyectora, Características hidráulicas y de empuje, Coeficiente de presión.

ABSTRACT

Water-jet propulsion pump produces an action force by the flow of water at the outlet that is under a free water state when it does not suffer from constraints resulting from a pipeline or valve error, its thrust characteristics are also influenced by water flow characteristics. The calculation and experiment models of the hydraulic and thrust characteristics of a miniature water-jet propulsion pump were proposed in this study in order to determine the relationships between the hydraulic and thrust characteristics of the water-jet propulsion pump. We established the hydraulic calculation model by using the velocity coefficient method and thrust prediction, whereas the experiment model under open state was established by combining the working characteristics of the water-jet propulsion pump. The pressure coefficient at the outlet of the water-jet propulsion pump, velocity distribution at the outlet section, thrust characteristics under different revolution speeds, and the dynamic characteristics of different distances from nozzle to pool bottom were studied based on fluid dynamics and momentum theorem, after which model accuracy was verified through the experiment. Results show that the flow of the miniature water-jet propulsion pump presents a linear relationship with elevated pump revolution speed, and that the area of axial velocity being smaller than or equal to −1.5 m/s has positive correlations with both the revolution speed and the distance from nozzle to pool bottom. Results also indicated that the thrust of the miniature water-jet propulsion pump is influenced by the distance from the nozzle to the bottom: when the distance is greater than 0.8 m, the experiment pool has no influence on the thrust of the water-jet propulsion pump. This research results are of great significance in establishing a experiment stand of a miniature water-jet propulsion pump and its performance evaluation.

Keywords: Water-jet propulsion pump, Hydraulic and thrust characteristics, Pressure coefficient.

1. INTRODUCTION

Water-jet propulsion pumps are typically used in high-speed high-performance ships, amphibious vehicles, and shallow-draft ships due to their advantages, such as small turning radius, low intra-cabin noise and vibration, high propulsive efficiency, favorable anti-cavitation capacity, flexible maneuverability, small resistance, minor shallow water effect, as well as simple structure and maintenance [1]. The demand for water-jet propulsion pump applications has gradually increased. In recent years, relevant technical studies have made considerable progress, and more stakeholders have participated in various links—research, design, production, and application—of water-jet propulsion pumps. The mixed-flow type and axial-flow type system are used for most water-jet propulsions [2]. The Woods Hole Oceanographic Institution in the US developed an offshore underwater autonomous vehicle, which realized advancing and steering through water-jet thruster, thus realizing the application of water-jet propulsion to underwater vehicles [3].

However, with the development of the long-term operation of underwater vehicles, water-jet propulsion pump engineers have developed a miniature type that features better water-jet propulsive efficiency. In order to improve the thrust performance of the water-jet propulsion pump, the head at its nozzle has become increasingly lower, with the head during its design process being generally below 0.5 m. Its thrust characteristics involve many factors that contribute to technical difficulties; in turn, such challenges have brought about enormous challenges to researchers focusing on water-jet propulsion pumps.

Based on such developments, researchers have carried out studies on the influences of the revolution speed and geometric parameters of impellers of miniature water-jet propulsion pumps on hydraulic and thrust characteristics [4–7]. However, the hydraulic and thrust calculation models of miniature water-jet propulsion pumps and their mutual coupling relationship still deviate from the actual working state. Hence, two problems require urgent solutions: (1) accurately predicting the hydraulic and thrust characteristics, and (2) defining the mutual coupling relationship between them in the actual operating state of the water-jet propulsion pump.

On this basis, we established in this study a finite element calculation models of the hydraulic and thrust characteristics of a miniature water-jet propulsion pump using the velocity coefficient and finite element methods. The pressure coefficients as well as thrust and flow characteristics at the outlet of the water-jet propulsion pump were analyzed, with the aim of accurately predicting the hydraulic and thrust characteristics as well as their mutual coupling relationship more accurately. In doing so, we provide reference for the development and optimization of miniature water-jet propulsion pumps.

2. STATE OF THE ART

At present, researchers have carried out numerous studies on water-jet propulsion pumps used for ships. Bulten [8–10] used a mature numerical simulation technique to study the hydrodynamic performance of an inlet conduit and an entire pump system, but was unable to provide a detailed research analysis of fluid characteristics at the nozzle. Kandasamy [11–12] proposed a complete computational fluid dynamics (CFD) model for water-jet propulsion, and studied the mutual influence between hulls and water-jet system, but the model was not applicable to jet flow state with low outlet flow velocity. Aldas [13] studied the influences of absolute and relative roughness on pump efficiency, and found that CFD was the most appropriate tool for conducting research on a jet pump model; however, the author did not study fluid characteristics at the outlet. Meanwhile, Wu [14] measured flow structures, concentrating on the tip region of a water-jet propulsion pump rotator through particle image velocimetry (PIV) under different resolutions, including summary process of tip clearance flow, and tip leakage vortex. However, the author did not analyze the fluid characteristics at the outlet. In order to solve key problems in the early design phase of high-speed ships (i.e., selection of propulsion system and performance prediction), Altosole [15] proposed two dimensionless numerical programs that can determine whether water-jet propulsion worked at the designed point and if the effectiveness and accuracy of the performance evaluation method of a water-jet propulsion system can be verified. However, the author found that the dimensionless numerical programs were not appropriate for miniature water-jet propulsions. Chang [16] studied the key parameters of inlet and impeller clearance in a water-jet propulsion system and predicted flow in the clearance region, but did not study its hydraulic characteristics. Ding [17] calculated the inlet and stern flow field by CFD methods and comprehensively evaluated fluid dynamic performance of the inlet conduit with multiple indexes, including effluent uniformity, flow separation degree, cavitation degree, flow loss degree, and applicability of variable working conditions. Jin [18] designed a water-jet propulsion pump by using a 3D method, and then he designed a conduit using a parametric design method; the author then verified the fluid dynamic performance of the newly designed water-jet thruster by numerical experimentation method. Cao [19–21] analyzed the influences of the second-stage diffuser, number of blades, position where blades flew towards the circulation center, and circulation at the blade outlet on the performance of a water-jet thruster via a CFD diffuser. Ma [22] studied the design methods of conduit, impeller, and diffuser of water-jet pumps, the results of which provided references for the integral design of water-jet propulsion pumps.

The above-mentioned studies mainly concentrated on the blade design methods and internal flow characteristics of water-jet propulsion pumps used for ships, but only few studied their dynamic characteristics, especially the correlation among the thrust characteristic tests. Velocity coefficient method and CFD method are used in the current study to establish the calculation model of the hydraulic and thrust characteristics of miniature water-jet propulsion pumps. This article discusses the internal flow characteristics of a water-jet propulsion pump, the characteristics of water-jet propulsion pump under different working conditions (i.e., pressure coefficient of outlet, different revolution speeds and different distances from the nozzle to the pool bottom), and the coupling relationship between the hydraulic and thrust characteristics. The results of this study can provide bases for the optimization and testing of miniature water-jet propulsion pumps.

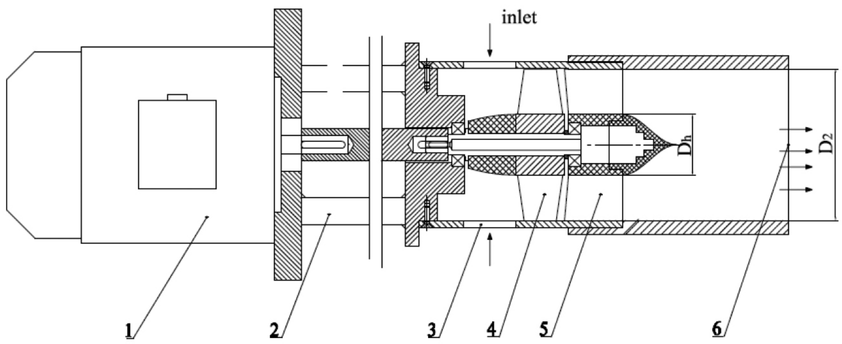
The rest of the study is arranged into sections. Section 3 describes the structure of the water-jet propulsion pump and establishes the calculation models of the hydraulic and thrust characteristics of the water-jet propulsion pump. Section 4 uses CFD to analyze the hydraulic and thrust characteristics of the proposed models as well as to obtain the coefficient distributions of the outlet pressure and internal flow characteristics at the nozzle under different working conditions. The final section summarizes this study and provides the relevant conclusions.

3. METHODOLOGY

3.1. PHYSICAL MODEL

The design parameters of the miniature water-jet propulsion pump included design flow quantity Q_{des} = 0.0089 m³/s, head H = 0.4 m, and revolution speed n_{des} = 104.72 rad/s. The geometric parameters included the impeller diameter of outlet D_2 = 0.112 m, hub diameter D_h = 0.05 m, number of impeller blades Z_i = 4, and number of diffuser vanes Z_v = 5. The model structural graph is shown in Fig. 1.

The water was fed to the water-jet propulsion from inlet with the momentum, after worked by the impeller and the diffuser, and drained from the outlet (nozzle) with the momentum. The thrust of the pump is generated by the diference from the axial momentum at the outlet to the axial momentum at the inlet.



Note: 1-Motor 2- Connecting frame 3-Inlet 4-Impeller 5-Diffuser 6-Outlet
Fig. 1: Structural scheme of the pump

3.2. CALCULATION MODEL

Pro/E was used to establish the model of the overflowing part of the water-jet propulsion pump, as shown in Fig. 2.

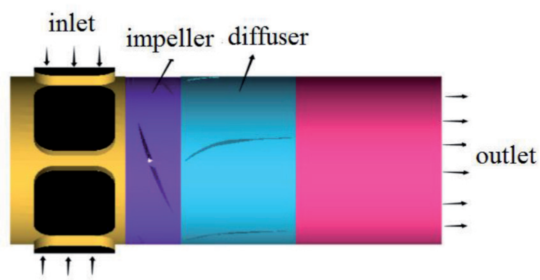


Fig. 2: Geometric structure of water-jet propulsion pump

To meet the requirement for calculation accuracy during and after CFD calculation process by CFX, the structured grid has been adopted for the pool and the blades of the impeller and diffuser, its grid irrelevancy should be studied. The change rate was 0.6% when the total number of grids was 1,247,000, in which the grids of the impeller, diffuser, inlet segment, and outlet segment reached 552,000, 411,000, 117,000, and 357,000, respectively, thus meeting the requirement for calculation accuracy. The grid structures of impeller and guide value are shown in Fig.3(a) and Fig.3(b) (see section: supplementary material), respectively.

3.3. CALCULATION METHOD AND BOUNDARY CONDITIONS

Reynolds-averaged Navier-Stokes (RANS) is extensively applied in the field of engineering. This was used in the current study to calculate turbulent flow of the water-jet propulsion pump, and the SST k-ω turbulence model was used to close the set of governing equations. SST k-ω turbulence model was simulated by invoking k-ε turbulence model in the near wall region with favorable convergence, and it was simulated by invoking the k-ω turbulence model in a fully developed turbulent region with high calculation accuracy. This turbulence model was appropriate for flow calculation of the rotary machine [23].

For the calculation of external characteristics, inlet condition was set as the total pressure, and outlet condition was set as mass flow field. The "Frozen Rotor" method where the rotor is supposed to be held with the rotation properties (the velocity of the solid surface boundary) but always at the same position in a steady-state simulation was used to ensure the rotor–stator interactional surface between impeller and diffuser, and smooth non-slippage wall function was used.

Under thrust calculation, the actual operating state of the water-jet propulsion pump is an open state, that is, there is no flow regulation device like a valve at the outlet conduit, and at the moment, flow quantity of the pump is unknown and is only related to pipe resistance. However, flow quantity is an important evaluation index for evaluating the pump performance parameters; thus, the CFD should be used to solve relevant parameters like flow quantity so as to explore the dynamic characteristics of the pump under this working condition. To calculate the relevant parameters of the pump under actual working conditions, the computational domain as shown in Fig. 4 was selected as geometric calculation model in accordance with the relevant calculated data of the water-jet propulsion pump [24]. h is the distance from nozzle to the bottom. This would not affect calculation accuracy, and there would be relevant data support in the following section. The calculation method adopted in the CFD calculation process is similar to the abovementioned calculation method. However, they also differ in the sense that the calculation method adopts free boundary condition to process the interface between water and air, where relevant pressure is then set as a standard atmospheric pressure. For grid division, the quantity and mass of grids of the pump remained unchanged, and the number of grids for water pool was added, which could effectively meet the requirement for calculation accuracy.

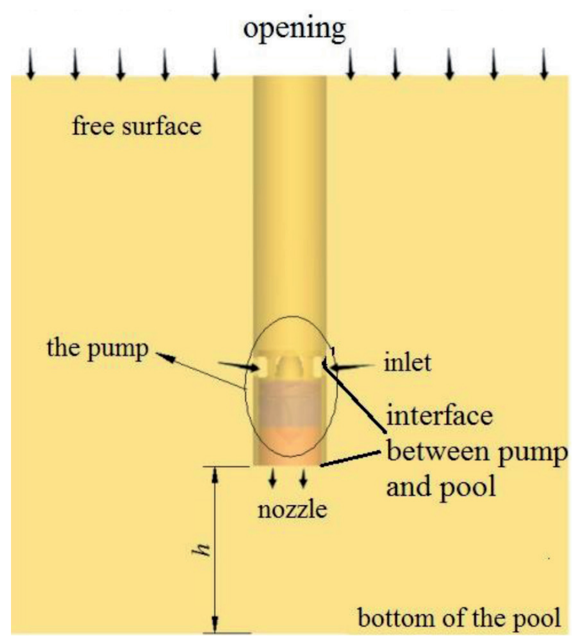


Fig. 4: The computational domain of thrust

3.4. PRESSURE COEFFICIENT

Pressure coefficient was used to judge flow characteristics and disturbed flow intensity at the pump outlet. In doing so, we obtain a comprehensive reflection of the variation rule of static pressure.

$$C_P = 2\left(P_{out} - P\right) / \rho V^2 \tag{1}$$

In the formula, P_{out} is the static pressure at the outlet section of the pump, Pa; P is hydrostatic pressure at the depth of the pump outlet, Pa; and V is the average axial velocity inside impeller, m/s.

3.5. JUDGING CRITERION OF THRUST

According to the thrust analysis of the water-jet propulsion pump, its total thrust can be divided into two parts: thrust F_v caused by velocity change, and thrust change caused F_H by pump head. Hence, the total thrust of the pump can be expressed by Formula (2).

$$F = F_v + F_H \quad (2)$$

In the formula, F_v can be obtained according to momentum theorem, and the specific expression is shown in Formula (3).

$$F_v = \rho Q(v_{2m}\text{-}v_{1m}) = \rho A v_{2m}(v_{2m}\text{-}v_{1m}) \quad (3)$$

In Formula (3), v_{1m} is the axial velocity at the inlet of water-jet propulsion pump, m/s; v_{2m} is the axial velocity at the outlet of water-jet propulsion pump, m/s; ρ is the liquid density, kg/m^3; Q is the volumetric flow of the pump, m^3/s; and A is the sectional area of the outlet, m^2. Given that the inflow direction of the water-jet propulsion pump studied in this thesis subject is radial, the axial component velocity at the inlet is zero, that is, $v_{1m} = 0$.

Thrust change caused by the pump head can be expressed by Formula (4).

$$F_H = \rho g H A \quad (4)$$

In Formula (4), H is the pressure head at the section outlet of the pump. The thrust performance of the water-jet propulsion pump is one of the main evaluation indexes of its dynamic characteristics and thrust, which can directly influence navigational speed of the pump. Therefore, obtaining accurate data on the thrust performance of the pump is the research emphasis of this study, in which the change of the distance from nozzle to pool bottom and change of pump revolution speed are the main factors influencing thrust performance experiment. These will be analyzed mainly from two aspects discussed below.

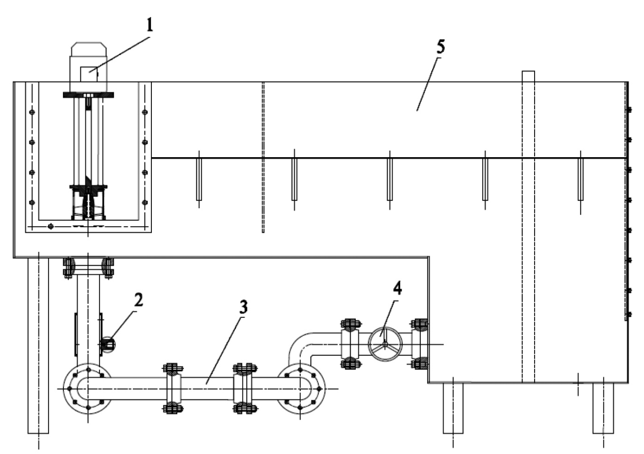
The efficiency of the pump with the machine at rest can be expressed by Formula (5).

$$\eta = \frac{\rho g Q H}{p} \quad (5)$$

In Formula (5), p is the shaft power of the pump.

3.6. EXPERIMENTAL MODEL

The experiment stand of hydraulic performance was built according to the inlet characteristics of the water-jet propulsion pump, as shown in Fig. 5. As can be seen, the pump was vertically



Note: 1-The water-jet pump 2- The pressure 3- The flow rate 4- The control valve 5-The pool
Fig. 5: Experiment stand of hydraulic performance

secured, its inlet was immersed into the water in water pool, and the outlet consisted of pressure gauge, flow meter, and valve.

Thrust performance is a main characteristic of a water-jet propulsion pump. In the current study, thrust was measured according to weighing principle; it consisted of tension sensor, height-adjustable connecting rod, and supporting rod, as shown in Fig. 6. The required sensors during the experiment process included high-precision S-shaped tension sensor and torque sensor manufactured by USA FUTEK corporation, and their measurement accuracies were ±0.5% and ±0.2%, respectively. Here, tension sensor and height-adjustable connecting rod adopted rigid connection, which was also used between torque sensor and tension sensor and between torque sensor and dual connecting rods, thus effectively reducing system error values of the experiment device and ensuring measurement accuracy.

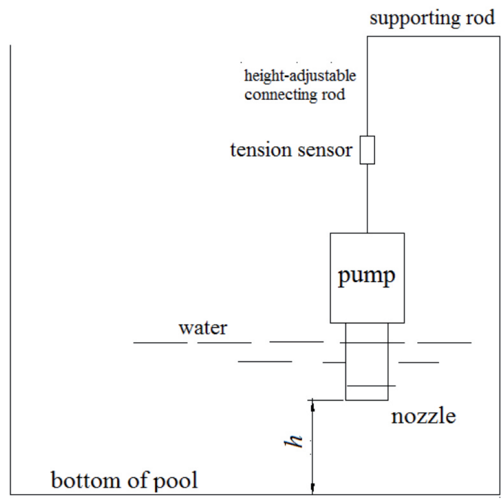


Fig. 6: Thrust performance experiment device of the pump

4. RESULT ANALYSIS AND DISCUSSION

The external characteristic curve was obtained (Fig. 7) through the calculation of the internal flow of miniature water-jet propulsion pump under different working conditions. The calculated results were compared with the experiment results. Under the designed working condition, pump head was 0.46 m and the error was 4.17% compared with the experiment head (0.48 m). Meanwhile, calculation efficiency was 58.03%, and the error was 4.90% compared with experiment efficiency (55.32%). Other calculated working conditions also met the requirements for engineering calculation accuracy. Hence, the CFD calculation results obtained in this study could accurately predict the internal flow distribution of the pump.

Meanwhile, the thrust characteristics of the modeled pump were tested by using the above thrust experiment device. The thrust characteristic curve shown in Fig. 8 is obtained, in which the dotted line represents the CFD calculation result expressed by the nozzle thrust of the water-jet propulsion pump. Based on Newton's third law, thrust at the moment should be equal to the tested result of the experiment device in the figure but should also have a reverse direction. As shown in the figure, the CFD-calculated curve has the same change rule as the experiment curve, and both present a gradually increasing trend. Meanwhile, as shown in the table, when h =0.5 m, maximum error is 4.64%, which meets the requirement for calculation accuracy. Thus, the numerical simulation results could accurately predict the thrust characteristics of water-jet propulsion pump.

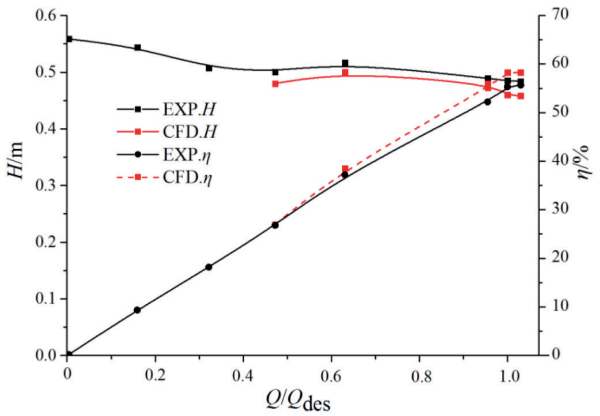


Fig. 7: External characteristic curves of CFD and experiment

4.1. PRESSURE COEFFICIENT DISTRIBUTION

As shown in Fig. 9(see section: supplementary material), the distribution of pressure coefficient C_P on the pump outlet section is not uniform. Meanwhile, a high-pressure zone under uniform distribution appeared near the diffuser and range of high-pressure zone, thus presenting a continuously decreasing trend as operating conditions intensified. When flow quantity is 1.0 Q_{des}, pressure showed favorable regularity, and the range of low-velocity zone under uniform distribution is small. When the pump operated by deviating from the designed working condition, the non-uniformity of C_P would be enlarged regardless of whether the operating flow quantity is increased or decreased. Here, C_P value is great under small flow quantity. Moreover, based on the thrust calculation formula of water-jet propulsion pump, the thrust at the moment increased but not vice versa.

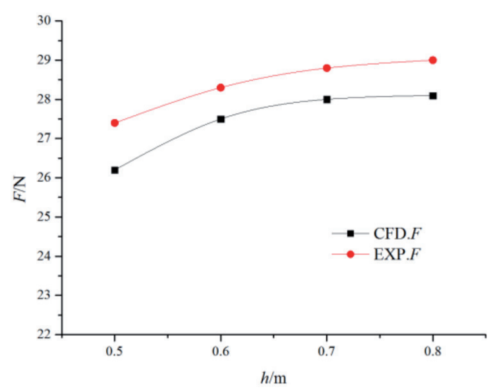


Fig. 8: Thrust characteristic curves of CFD and experiment

4.2. VELOCITY DISTRIBUTION AT THE WATER-JET PUMP OUTLET

Fig. 10 (see section: supplementary material) shows axial velocity distribution on the outlet section of water-jet propulsion pump under different operating conditions; the negative sign in the figure represents an opposite direction to the reference direction. As shown in the figure, when the pump operates under a small flow quantity, the velocity distribution range on pump outlet section is small with obvious non-uniformity and obvious low-velocity zone. As the operating flow quantity of the pump increased and when the pump operated under designed working condition, the low-velocity zone becomes obviously smaller, axial velocity distribution becomes relatively regular, and flow ability is more favorable. When the pump operates under a large flow quantity, deviating from the designed working condition, an obvious high-velocity zone appears in the figure with obvious asymmetry. When the pump operates under a small flow quantity, average axial velocity becomes small, which reduces the outlet thrust under the same pressure and not vice versa.

4.3. INFLUENCE OF DIFFERENT REVOLUTION SPEEDS ON THE THRUST CHARACTERISTICS OF THE PUMP

During the calculation of the thrust experiment of water-jet propulsion pump, the pump outlet was under a full-open state. When pump revolution speed changed, flow quantity would also change, along with the influencing range of the flow field at the pump outlet and its thrust characteristics.

Fig. 11 (see section: supplementary material) displays the relationships between axial velocity distribution at the nozzle and pump revolution speed, in which the negative sign represents reverse direction to direction of reference coordinate. As shown in the figure, after the fluid flows out of the pump, the influencing range of axial velocity would enlarge as pump revolution speed increases. When $n = 0.6n_{des}$, axial velocity presents an axial symmetrical distribution, and the influencing range could reach pool bottom, although the influencing width becomes relatively narrow. A local low-velocity zone appears nearby the nozzle, and this zone continuously expands as pump revolution speed increases, especially when $n = 1.2n_{des}$. Pump revolution speed could even influence pool bottom, which in turn, can influence the thrust performance of water-jet propulsion pump. Hence, during the thrust experiment of the water-jet pump, the depth of the deep pool should be increased to ensure that the bottom flow of the pool would not affect the thrust performance of the pump.

4.4. INFLUENCE OF DIFFERENT DISTANCES FROM THE NOZZLE TO THE POOL BOTTOM ON THE DYNAMIC CHARACTERISTICS OF THE PUMP

Fig. 12 (see section: supplementary material) shows the influence of the distance h from the nozzle to pool bottom on the axial velocity of the water-jet pump under rated revolution speed. The specific meaning of h is seen in Fig. 8. As shown in the figure, under fixed pump revolution speed, the influencing range of the axial velocity at the nozzle increases as the height increases. The height in the area with axial velocity V_z being smaller than or equal to −1.5 m/s is also related to h , that is, the greater the value of h, the greater the height. However, change rate is relatively low, and such a height would remain unchanged when h further increases. When h = 0.5 m, obvious reflective flow phenomenon occurs in the pool bottom, and its influencing zone could nearly extend to the area near the pump inlet; moreover, its influencing range obviously decreased as h continuously increased. Therefore, the design of the thrust experiment device of the water-jet pump should guarantee the necessary h value. For the research object of this study, the experiment requirement could be met only when h is greater than 0.8 m.

4.5. THRUST DISTRIBUTION AT THE NOZZLE OUTLET

Calculated data were processed according to Formula (2), and cloud atlas on the nozzle section under different h values were obtained as shown in Fig. 13 (see section: supplementary material). As can be seen, the distribution of transient thrust $\overline{F}$ at the nozzle presents the change rule of "large outside and small inside," which is in accordance with the axial velocity analysis in the last section. In addition, as h increases, internal thrust continuously increases, but during the change process from h = 0.7 m to h = 0.8 m, the change of this value is not very obvious. Through weighted average processing of thrust $\overline{F}$ on different sections, change process of thrust $\overline{F}$ during change process from h = 0.7 m to h = 0.8 m could be obtained, as shown in Table 1, in which $\bar{\delta}$ refers to the change rate of $\overline{F}$ value.

As h increases, $\overline{F}$ continuously increases and $\bar{\delta}$ continuously decreases. By assessing the change trend, we can say that when h infinitely increases, $\overline{F}$ would not change and $\bar{\delta}$ would be zero, thus meeting the verification of the thrust irrelevancy of water-jet pump. During the actual experiment process, due to restrictions by the experiment field and experiment cost, h would not infinitely increase. However, after a fixed value is given, its influence on thrust characteristics could be neglected. For the research object in this study, when h = 0.8 m, it could be approximately considered that the pool has no influence on the thrust characteristics of the pump at the moment.

H (m)	0.5	0.6	0.7	0.8
$\overline{F}$ (N)	27.43	28.49	28.97	29.07
$\bar{\delta}$ (%)	-	3.64	1.68	0.35

Table I: Relation by average processing of thrust and the distances

5. CONCLUSIONS

In order to explore the characteristics of a miniature water-jet propulsion pump and determine the relationships between the hydraulic and thrust characteristics of the water-jet propulsion pump, starting from the physical model of the water-jet propulsion pump, the integral method of numerical simulation technique and experimental research are adopted in this study. This procedure is carried out in order to analyze pressure coefficient as well as the thrust and flow characteristics at the outlet of the water-jet propulsion pump. Finally, the following conclusions were obtained:

(1) A high-pressure zone appeared near the diffuser of the water-jet propulsion pump, and the area of high-pressure zone is inversely proportional to thrust.

(2) Velocity at the outlet section of the water-jet propulsion pump is obviously not uniform with the low-velocity zone. Moreover, the area of the low-velocity zone is inversely proportional to flow quantity and thrust of the water-jet pump.

(3) Axial velocity at the outlet of the water-jet propulsion pump presents a symmetrical distribution, and the influencing range of the pool is consistent with the nozzle size. When the distance from the nozzle to the pool bottom reaches 0.8 m, thrust would not be influenced.

With experimental research and numerical calculation, the calculation models of the hydraulic and thrust characteristics were proposed in this study, and the established models were simplified in accordance with the actual situation. Thus, the results can serve as a reference in the establishment of the experiment device of a miniature water-jet propulsion pump and its optimized research. Due to the lack of actual data on hydraulic characteristics under a thrust state, hydraulic measurements will be implemented in a future research, with the aim of achieving a more accurate thrust design of the water-jet propulsion pump.

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APPRECIATION

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SUPPLEMENTARY MATERIAL

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