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Hydrodynamic Analysis of Water-jet Thrusters for the Spherical Underwater Robot (SUR III)

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Abstract – **For the propulsion system of an underwater robot, the nozzle of the water-jet thruster plays an important role in converting energy to generate the reaction thrust. In order to achieve a higher reaction thrust, hydrodynamic analysis of the water-jet thruster is introduced in this paper. First, the prototypes of the third-generation Spherical Underwater Robot (SUR-III) and the water-jet thruster are given. Then the design principle of conical nozzle is described in detail. The shape of nozzle is changed from the traditional cylindrical one to conical one. The control angle is used to change the reaction thrust of the water flow in the outlet of nozzle. Before making the hydrodynamic analysis, we use Solidworks2011 to establish 3D models of conical nozzles with different control angles. Some unimportant parts causing limitations are ignored to simplify the analysis. Finally, ANASYS CFX is employed to make the hydrodynamic analysis. Comparing the simulation results with theoretical values, the velocity error is less than 6.64%. The simulation results show that the increase of control angle of conical nozzles can increase the reaction thrust of water-jet thruster. Meanwhile, the reaction thrust of conical nozzle with 20° control angle is more than two times as big as that of cylindrical nozzle.**

Index Terms – Spherical Underwater Robot, Water-jet Thruster, Conical Nozzle, Hydrodynamic Analysis, ANASYS CFX

I. Introduction

With the development of economy and science technology, various kinds of underwater robots have been developed to meet the requirements of different tasks over the past several decades. Usually, the underwater robots are divided into two categories: Remote Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). ROVs are working robots that can sneak into the water to complete some certain operations under people's control [1]. But facing a complex environment, ROVs can't make the initiative corresponds. While AUVs have unique advantages in submarine resource exploration, underwater equipment maintenance, target detection or rescue missions, whether in civil field, commercial field, educational and scientific field or military field [2][3]. The underwater robots have been developed, using an assortment of shapes, sizes, weights, and propulsion systems. Spherical underwater robots are the most special ones, because they can make an outstanding performance on water-resistance, resulting in easily implementing a rotational motion with a 0° turn radius.

Combining the advantages with task requirement, many researchers have realized their own spherical robots. Researchers at Harbin Engineering University developed a spherical underwater robot which adopted three water-jet thrusters as its propulsion system [4][5]. This design has some advantages: Low vibration noise and high promotion efficiency. In our laboratory, Reference [6] first proposed the concept of vectored water-jet propulsion, which can be adopted in the spherical underwater robots. And on the basis of this idea, a novel spherical underwater robot had been realized and analyzed [7]-[9]. And other researchers in our laboratory continued to make improvements [10]-[21]. However, there are some common shortcomings in their methods. In other words, the speed is not fast enough under same conditions, as well as the reaction thrust. This paper focuses on the improvement of water-jet thrusters in order to increase the speed and driving force of propulsion system.

Hydrodynamics studies the movement of the liquids and their interaction with the boundaries. Usually, according to the hydrodynamic analysis, we can get the liquid resistance and other valuable characteristics. Through Computational Fluid Dynamics (CFD), Reference [22] proved that blade tip loading can be reduced in order to restrain the cavitation of sheet and tip vortex, resulting in low noise and better protection from surface erosion. Reference [23] made a comparison between Kappel propellers with conventional propellers, hydrodynamic analysis emphasizes the superior performance of Kappel propellers with end-plate effects. Reference [24] made a computational numerical analysis of different nozzles, mainly including cos, exponent, cylindrical and conical ones. The effects of geometric and dynamic parameters of different nozzles on the outlet velocity and pressure map are analyzed

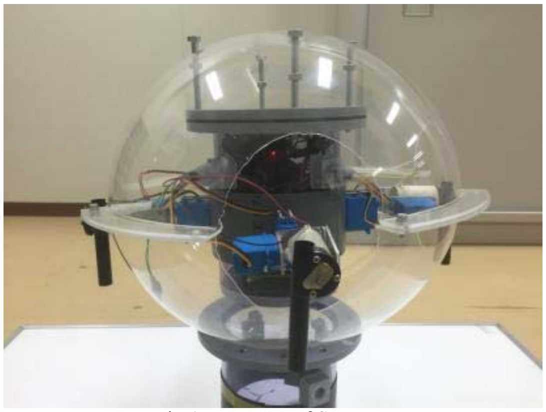


Fig.1 Prototype of SUR-III.

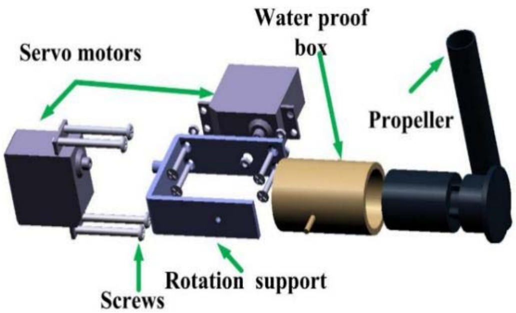


Fig.2 Assembly model of the water-jet thruster system.

in detail. The study result privates us a good theoretical basis for the research of nozzles in the water-jet propulsion system for underwater robots. In our laboratory, Reference [25][26] analyzed the hydrodynamic characteristics of the second-generation Spherical Underwater Robot with ANASYS FLUENT software and verified the drag coefficients for horizontal and vertical motions. Hydrodynamic analysis showed that simulation results were very close to the theoretical values. More relative information can be found in References [27]-[29].

The structure of this paper is organized as follows. In the section I, the background and purpose of the study are introduced. In the Section II, the 3D model of conical nozzles in water-jet thruster and the design principle of conical nozzle are presented. ANSYS CFX-based hydrodynamic analysis of conical nozzles are shown in the Section III. Finally, the conclusion and future work are given in the Section IV.

II. Modeling of Conical Nozzle of Water-jet Thruster

A. The Prototype of SUR-III and Water-jet Thruster

In our laboratory, the second-generation Spherical Underwater Robot(SUR-II) takes three vectored water-jet thrusters as its propulsion system, resulting in 3 DOF motions [30][31]. However, the energy consumption of SUR-Ⅱ is high and the max velocity just can up to 0.3m/s. So the third-generation Spherical Underwater Robot (SUR-Ⅲ) is developed with four water-jet thrusters, as shown in Fig.1. SUR-Ⅲ is made up of two hemispheres, fours water-jet thrusters, waterproof box and the control center. The angle between each thruster is 90 degrees. One water-jet thruster system consists of a motor, two servos, a water proof box, the rotation support and a nozzle, as shown in Fig.2.

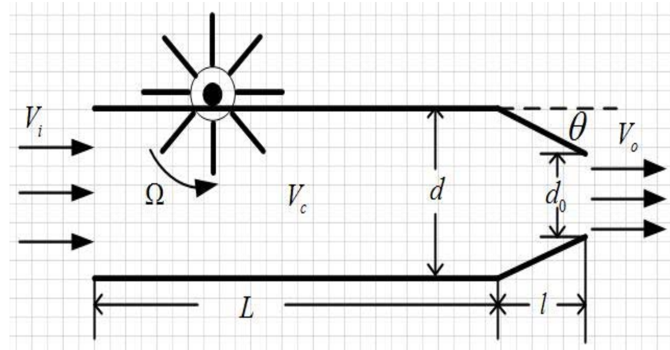


Fig.3 Sketch of the conical nozzle.

B. Design Principle of Conical Nozzle

In order to achieve a higher velocity and reaction thrust of the propulsion system, the design principle of the conical nozzle is given in this section. For the convenience to illustration and calculation, we make some assumptions as follows:

1) Assume that the liquid flow can't be compressed, so the density is same for all units, ρ represents the density of liquid flow.

2) Ignore the thickness of nozzle and simply analyze the effect of its inner wall instead.

As shown in Fig.3, the sketch of the simple thruster is given. From this Fig, we try to change the structure of nozzle from cylindrical shape to conical one. θ is the control angle.

Case 1: $\theta = 0$.

At this time, the nozzle is cylindrical. According to the equation of continuity, the following equation can be obtained [32]:

$$\rho A_c V_c = \rho A_o V_o \quad (1)$$

where V_o represents the outlet velocity of nozzle and V_c represents the velocity after the water flows through the blade. A_c and A_o represent the flow cross-sectional area at the centre and outlet of the nozzle, respectively. Under this circumstance, the nozzle is cylindrical, so we can get:

$$A_c = A_o, V_c = V_o \quad (2)$$

Case 2: $\theta > 0$.

At this time, the nozzle is conical. In order to achieve a higher velocity of the propulsion system, we make a novel improvement and design of the nozzle. According to "(1)", we can see if the flow cross-sectional area at the outlet port of nozzle can be reduced, a higher velocity could be achieved. Sacrificing a part of the export volume, we can obtain a greater reverse driving force. Now, equation (1) can be transformed into the following equations:

$$\frac{V_o}{V_c} = \frac{A_c}{A_o} = \frac{d^2}{d_0^2} \quad (3)$$

$$d_0 = d - \frac{2l}{\cot\theta} \quad (4)$$

where d_0 represents the diameter of the outlet and θ is the angle between inner wall and inclined surface, we call it control angle. l is the horizontal distance we choose to start changing the position of the structure.

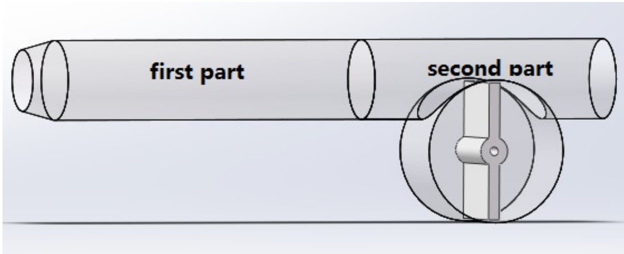


Fig.4 Simply model of thruster.

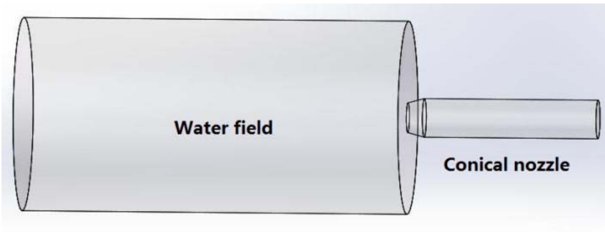


Fig.5 3D model of conical nozzle.

Table I Value of each parament

parameter	L	l	d	V_i	Ω
value	63.2mm	6mm	14mm	0.3m/s	400r/m

According to the pressure theorem, the reaction thrust generated by the nozzle can be expressed as:

$$F_T = \Delta P * A_o = (P_o - P_i) * A_o \qquad (5)$$

where P_o and P_i is the pressure of the outlet and inlet of the nozzle, respectively.

According to the Bernoulli's equation, we can combine the pressure with velocities of the inlet and outlet. The total pressure of inlet and outlet are as follows:

$$P_{ti} = P_s + 0.5\rho V_i^2 \qquad (6)$$

$$P_{to} = P_s + 0.5\rho V_o^2 \qquad (7)$$

where P_s represents the static pressure. Combining the above equations, we can get the final reaction thrust.

$$F_T = 0.5\rho A_o (V_o^2 - V_i^2) \qquad (8)$$

The values of the relevant parameters of the nozzle are shown in Table. I. (Ω represents the rotation velocity of motor shaft.)

C. *Modeling of Conical Nozzle*

The water-jet thruster consists of two servo motors, a water proof box, a rotation support, many screws and a nozzle. But what we focus on is the effect of control angles on the propulsion system. As shown in Fig.4, the thrust model is made up of two parts. One part is fixed with the motor which is connected with another part and the two parts are assembled freely. Actually, in our laboratory, Reference [26] had done the hydrodynamic simulation of the cylindrical nozzle (That is, control angle is equal to zero degree.). So, we only take the conical nozzle as the key objective in our research.

At the same time, we build a cylindrical water field ahead the outlet of the nozzle, as shown in Fig.5. The diameter of water field is set 5 times of nozzle's diameter and the length is 2 times of nozzle's total length. So, the effect of water field on the water flow of nozzle outlet can be ignored. All 3D models are done in Solidworks2011 software.

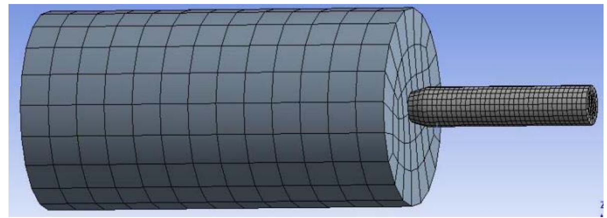


Fig.6 Mesh of conical nozzle.

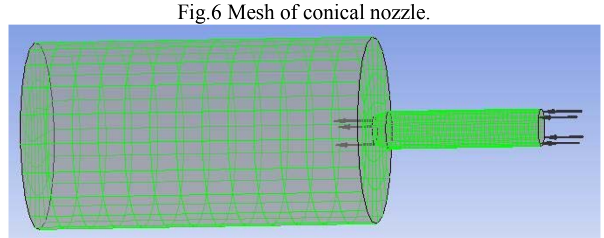


Fig.7 Setup operation of conical nozzle.

D. *Mesh of Conical Nozzle*

The mesh of the conical nozzle is an important step before analyzing the hydrodynamic characters. Among this, the quality and amount of grid are two main factors that determine the effect of our hydrodynamic analysis. In this subsection, we will discuss the mesh and set-up of the conical nozzle.

As shown in Fig.6, the mesh of the conical nozzle is given. The mesh of these simplified models is done in ANSYS ICEM. A total of 22799 elements is generated in our study. A good mesh has a very significant effect on the correctness of next simulation results. So, the calculation mesh should be set according to the corresponding requirements of the selected model. In order to get higher performance of hydrodynamic analysis, the size of mesh element should be reduced and get enough element. Next, we complete the set-up operation to determine the material and boundary conditions, as shown in Fig.7.

III. HYDRODYNAMIC ANALYSIS OF CONICAL NOZZLES

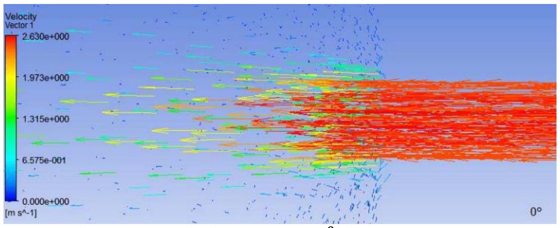
Since ANSYS software has combined many powerful functions, like ICEM, CFX, Fluent and so on. In this section, all the work is carried out in ANSYS Workbench. CFX analysis mainly consists of the following steps:

1) Import the 3D models of the conical nozzle into the Design Modeler.
2) Get the 3D model meshed in ICEM. The quality of mesh determines the performance of our hydrodynamic analysis.
3) Set up the initial conditions, including material conditions and boundary conditions.
4) Execute the solver.
5) Get the results of the solvers.

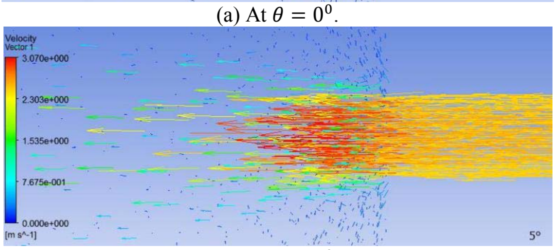
Because Reference [26] had done the simulation of the cylindrical nozzle and the outlet velocity is 2.5m/s. For the snake of simplicity and under the same conditions, we assume that the center velocity V_c is equal to this velocity. (That is to say that the inlet velocity is equal to the center velocity V_c.)

A. *Velocity Vector*

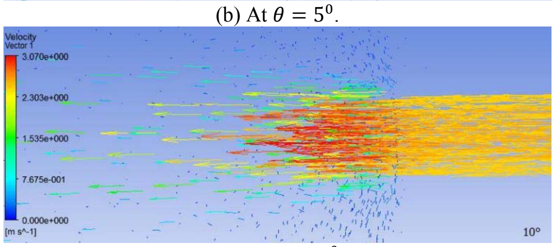
In the research, we not only change the structure of nozzle from cylindrical one to conical one, but also change the



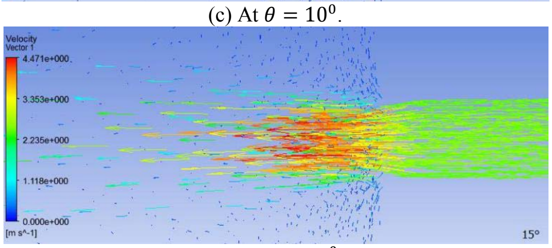
(a) At $\theta = 0^0$.



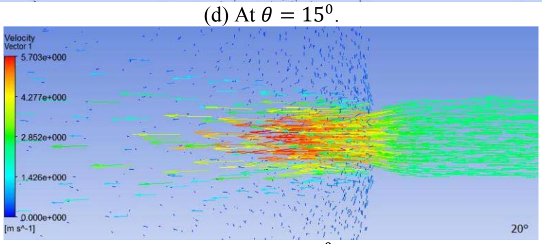
(b) At $\theta = 5^0$.



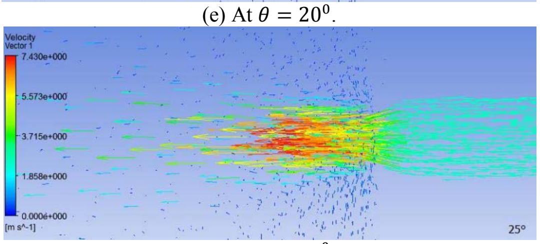
(c) At $\theta = 10^0$.



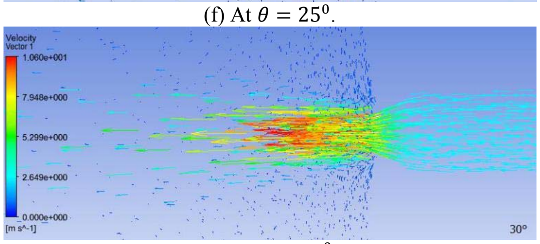
(d) At $\theta = 15^0$.



(e) At $\theta = 20^0$.



(f) At $\theta = 25^0$.



(g) At $\theta = 30^0$.

Fig.8 Velocity vectors of conical nozzles with different control angles.

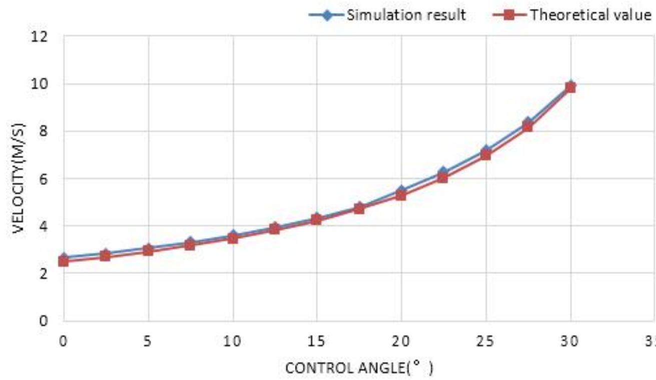


Fig.9 Differences between simulation results and theoretical values.

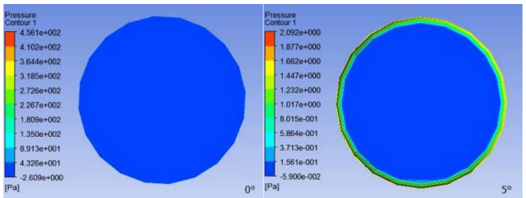
outlet velocity of the nozzle by the control angle. The velocity vectors of conical nozzles with different control angles (starting from 0°, 5° is plus each time.) are shown in Fig.8. From this Fig, we can see that the control angle is an important factor that affects the velocity of conical nozzles. With the increase of control angle, the outlet velocity becomes greater and the water flowing out of the outlet is more concentrated and less divergent. The difference between the simulation result and the theoretical value is shown in Fig.9 and the velocity error is less than 6.64%.

B. Pressure and Velocity Contours

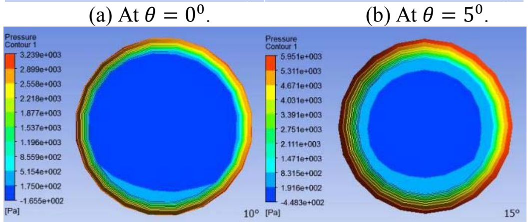
But the velocity is not the only factor we need to consider, the pressure on the inner wall of the nozzle is another important factor. Because the material of the nozzle is polyethylene plastic, the pressure it can withstand is limited.

The outlet pressures of conical nozzles with different control angles are shown in Fig.10. We can see that with the increase of the control angle, the pressure on the outlet of conical nozzles become larger. For a conical nozzle with a fixed control angle, the max pressure happens in the inlet and the min pressure happens in the outlet. The reason is that the water flow enters into the nozzle with a certain speed and flows out in the outlet smoothly. When the control angle is more than 20°, the pressure on the outlet of the nozzle increases rapidly. At the same time, velocity contours of the outlet are shown in Fig.11.

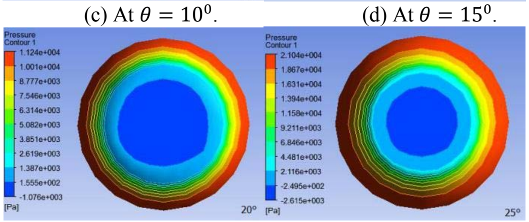
The smaller the control angle is, the greater the reaction thrust becomes. But as shown in Fig.12, when the control angle is more than 20 °, the pressure on the inner wall of nozzle has a sharp increase, which means structural strength must be taken into consideration. Thus, while increasing the outlet velocity and getting a greater reaction thruster, we must make sure that the pressure is within an acceptable range. The hydrodynamic analysis, mainly including velocity vector, pressure and velocity contours, shows the effects of the control angle on the outlet velocity, pressure and reaction thrust. Thus, it provides us great theoretical support to generate a greater reaction thrust. In our experimental environment, the most suitable control angle is 20°, the corresponding reaction thrust is 103.7% bigger than that of cylindrical nozzle.



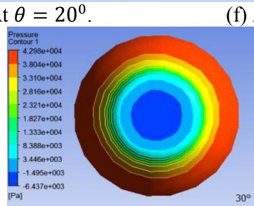
(a) At $\theta = 0^0$. (b) At $\theta = 5^0$.



(c) At $\theta = 10^0$. (d) At $\theta = 15^0$.

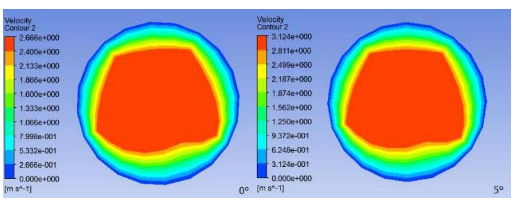


(e) At $\theta = 20^0$. (f) At $\theta = 25^0$.

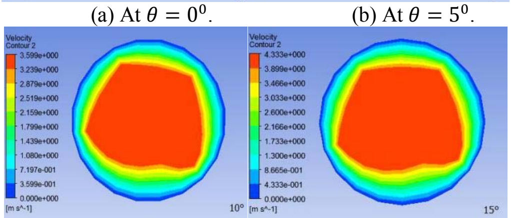


(g) At $\theta = 30^0$.

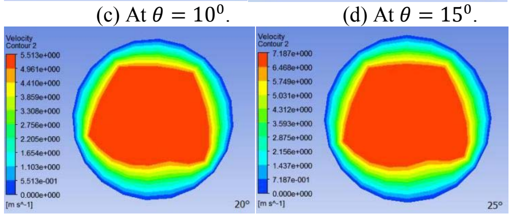
Fig.10 Pressure contours of nozzle outlets with different control angles.



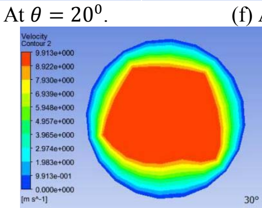
(a) At $\theta = 0^0$. (b) At $\theta = 5^0$.



(c) At $\theta = 10^0$. (d) At $\theta = 15^0$.



(e) At $\theta = 20^0$. (f) At $\theta = 25^0$.



(g) At $\theta = 30^0$.

Fig.11 Velocity contours of nozzle outlets with different control angles.

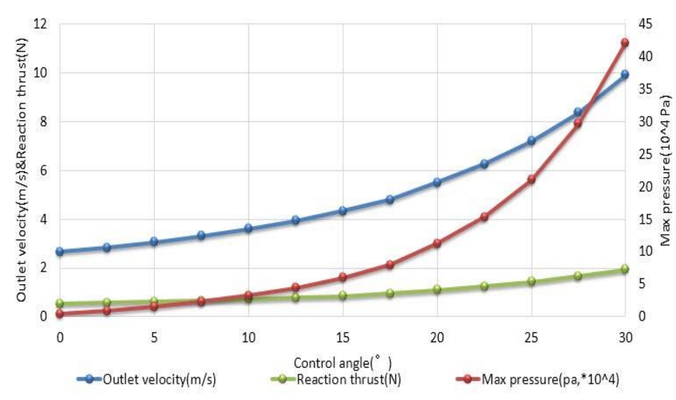


Fig.12 Overall simulation results.

IV. CONCLUSIONS

This paper introduces the hydrodynamic analysis of the water-jet thruster for the Spherical Underwater Robot SUR-Ⅲ. Conical nozzle, which is the main part to generate the reaction thrust, is the key object in our research. First of all, the prototypes of the third-generation Spherical Underwater Robot and the water-jet thruster are introduced briefly. The structure of nozzle is changed from the cylindrical one to conical one. Then detailed design principle of the conical nozzle is given. Some unimportant parts are ignored in order to reduce the impact of hydrodynamic analysis. We simplify and mesh the 3D models of conical nozzles with different conical angle in ANSYS ICEM. CFX provides us a series of simulation results of conical nozzles with different control angles for hydrodynamic analysis, mainly including the velocity vector, pressure and velocity contours. The difference error between the simulation results and the theoretical values is less than 6.64%. It provides us great theoretical support to find the balance point and determine the most suitable control angle. The results show that the increase of control angle of conical nozzle can increase the reaction thrust of water-jet thruster. In our experimental environment, the most suitable control angle is 20°, the corresponding reaction thrust is more than two times than that of cylindrical nozzle.

In the future, we will focus on quantitative simulations with more influencing factors. At the same time, the corresponding experiments will be carried out.

ACKNOWLEDGMENT

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