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OPTIMAL DESIGN OF THE TRANSFER DEVICE OF THE SURFACE THIN LAYER OIL SLICK BASED ON FLUENT AND BP NEURAL NETWORK

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In this paper, the feature-based parametric 3D - modeling technology of the pro/e 5.0 software was adopted to build virtual solid model of the bionics flow path. The bionics flow path is an major component of the transfer device of the surface thin layer oil slick. In the range of the parameters of the bionic flow path, to obtain 13 sets of sample points, the FLUENT numerical simulation tests arranged based on the uniform experimental design method. These sample points were used to obtain the structural parameters of bionics flow path of the optimum oil transfer efficiency by BP neural network. Finally, the factors that affect the transfer efficiency of oil slick transfer in bionic flow path are analyzed. The three-dimensional CFD simulation of the air-oil-water three-phase flow in the bionic flow path is developed. The results open up a road for the surface thin layer oil slick transfer and collection.

Keywords: Oil slick, Transfer and Collection, BP Neural Network, Uniform Experimental Design Method, FLUEN

1. Introduction

At present, Front-end interception & diversion and collection technology of surface oil slick [1-2], and the back-end oil-water separation technology of surface oil slick [3-4] has been mature gradually. However, the middle - end transfer technique, which transfers the oil-water mixture of contaminated water from the collection area to the oil-water separation equipment, is also in the exploration period of a narrow range of working conditions. Nowadays, the middle-end transfer technology and equipment are mainly applied to the large oil spill and the thick oil layer, but its application to the surface thin layer oil slick is very poor. In addition, with the increasing reliability and reliability of the simulation results of CFD software, it reduces the reliance on high cost manufacturing test models. Therefore, more and more CFD numerical simulation technology is applied to the early model design. With the background, this paper proposes a kind of oil slick middle-end transfer technique based on the bionic

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flow path of duck bill, which can be applied to the surface thin layer oil slick. The bionic flow path of the duck bill has the properties of preventing the back-flow of sewage and having better diversion effect [5]. To short design cycle and low test cost to find the optimal oil slick transfer efficiency of the equipment, the use of uniform design experiment method to select the number of sample points in the range of each structure parameters of bionic flow path. And the parametric 3D virtual modeling of bionic flow path is carried out based on the general hybrid surface function of pro/e 5.0. The output parameters corresponding to the 3D bionic flow in the sample points are obtained by using the VOF model in the CFD simulation software Fluent [6]. Then, the model of fitting sample points was established by using the nonlinear fitting ability of BP neural network in MATLAB. At last, the optimal structure parameters of the bionic flow path are found by the nonlinear optimization of genetic algorithm. In 2016, North China University of Water Resources and Electric Power and The Yellow River machinery factory of the Yellow River conservancy commission jointly developed a laboratory prototype based on this technology that successfully carried out the transfer test of the surface thin layer oil slick in the channel.

2. Structure Model

2.1. The Physical Model

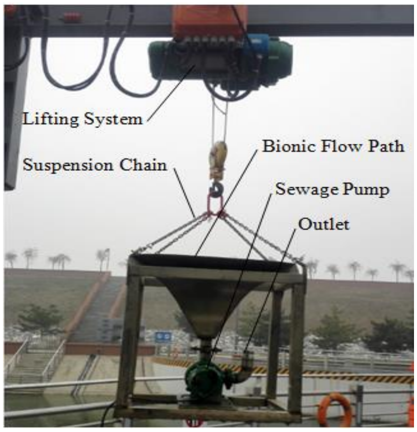


Figure1. The middle end transfer test device for the surface thin layer oil slick of South-to-North Water Diversion

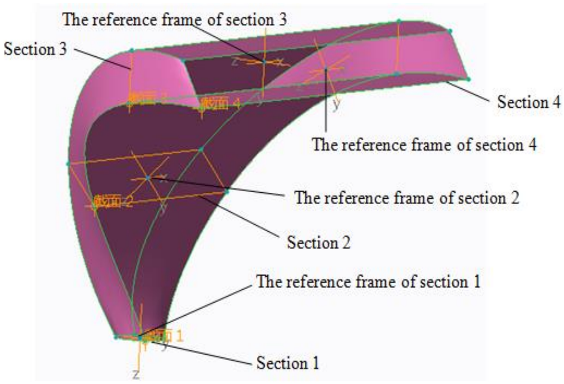


Figure 2. The physical model of the bionic flow path

Figure 1 is a middle end transfer test device for the surface thin layer oil slick of South-to-North Water Diversion, which is jointly developed by North China University of Water Resources and Electric Power and The Yellow River machinery factory of the Yellow River conservancy commission.

It is mainly composed of lifting system, suspension chain, bionic flow path, sewage pump, outlet pipe, pipeline and measuring control system. The feeding depth of the bionic flow path can be adjusted by improving the lifting system, which has certain robustness and can be applied to the oil layers of different thickness. The end of the suspension chain is linked by u-shackle, and the bionic flow path can be kept in balance by increasing or decreasing its quantity. The bionic flow path is made of duck's beak as a prototype, and bionic treatment is carried out to a certain extent. At work, the oil-gas - water mixture that flows into the bionic flow path is treated with a sewage pump that is elevated to a oil-water separator placed on the river embankment.

In this paper, the structure optimization and CFD simulation of the main link of the middle end transfer test device for the surface thin layer oil slick of South-to-North Water Diversion are presented in Figure 1. The physical model of the bionic flow path is built in pro/e 5.0 is shown in Figure 2. The lower end outlet parameter is φ60mm, and the upper entrance is 60mm. The other required parameters are as follows: the length of section 2 is L_1, the length of section 3 is L_2, the X-axis rotation Angle of the reference frame of section 2 is α, the X-axis rotation Angle of the reference frame of section 3 is 90°-α, the X-axis rotation Angle of the reference frame of section 4 is β, the depth between section 2 and section 1 is H_1, the depth between section 3 and section 2 is H_2, the depth between section 4 and section 3 is H_3.

2.2. Uniform Experimentation Design

The uniform experimental design is a new experimental design method proposed by our scientists on the basis of orthogonal experiment design. It only considers this feature of uniform distribution of the test point in the experimental range. So that the number of trials can be greatly reduced. But it did not reduce the representativeness of the data and successfully applied to the early missile design in China [7].

There are seven parameters to be optimized: L_1、L_2、α、β、H_1、H_2、H_3.

From m / 2 + 1 = 7, get m = 12, then n = m + 1 = 13, so choose U_{13}（13^{12}） table can minimize the number of tests. Taking into account the structural parameters of the test prototype and the reasonable experimental arrangement, the range of the 7 experimental variables is shown in Table 1.

Table 1.

The range of the experimental variables

Parametric variable	L_1/mm	L_2/mm	α/(°)	β/(°)	H_1/mm	H_2/mm	H_3/mm
The minimum value	120	604	30	-32	54	202	40
The maximum value	480	796	60	-8	246	298	100

According to the rules of the uniform experimental design U_{13} (13^{12}), the uniform experimental design schedule of the actual application is shown in Table 2.

Table 2.

The uniform experimental design schedule

No.	Column number（factors）						
	1 (L_1/mm)	2 (L_2/mm)	3 (α/°)	4 (β/°)	5 (H_1/mm)	6 (H_2/mm)	9 (H_3/mm)
1	1(120)	2(620)	3(35)	4(-26)	5(118)	6(242)	9(80)
2	2(150)	4(652)	6(42.5)	8(-18)	10(198)	12(290)	5(60)
3	3(180)	6(684)	9(50)	12(-10)	2(70)	5(234)	1(40)
4	4(210)	8(716)	12(57.5)	3(-28)	7(150)	11(282)	10(85)
5	5(240)	10(748)	2(32.5)	7(-20)	12(230)	4(226)	6(65)
6	6(270)	12(780)	5(40)	11(-12)	4(102)	10(274)	2(45)
7	7(300)	1(604)	8(47.5)	2(-30)	9(182)	3(218)	11(90)
8	8(330)	3(636)	11(55)	6(-22)	1(54)	9(266)	7(70)
9	9(360)	5(668)	1(30)	10(-14)	6(134)	2(210)	3(50)
10	10(390)	7(700)	4(37.5)	1(-32)	11(214)	8(258)	12(95)
11	11(420)	9(732)	7(45)	5(-24)	3(86)	1(202)	8(75)
12	12(450)	11(764)	10(52.5)	9(-16)	8(166)	7(250)	4(55)
13	13(480)	13(796)	13(60)	13(-8)	13(246)	13(298)	13(100)

3. Control Equation and Numerical Simulation

3.1. Control Equation

The process of collecting the oil slick in the bionic flow path is a process of oil-gas-water mixed fluid flow, which can be used to analyze the multiphase flow in the process of oil recovery by the more mature VOF method. By establishing the continuity equation and momentum conservation equation of each phase [8], the interphase interface tracing can be realized.

Continuity Equation:

$$\frac{\partial \alpha_q}{\partial t} + \vec{v}_q \cdot \nabla \alpha_q = \frac{S_{\alpha_q}}{\rho_q} + \frac{1}{\rho_q} \sum_{p=1}^{n} \left(m_{pq} - m_{qp} \right) \tag{1}$$

$$\sum_{q=1}^{n} \alpha_q = 1 \tag{2}$$

It is in continuality, α_q is the volume fraction of the q-phase fluid; m_{pq} is the mass transfer from the p -phase to the q-phase; m_{qp} is the mass transfer from the q-phase to the p -phase; S_{α_q} is the mass of the q -phase fluid in the control surface; $\vec{v}_q$ is the velocity vector of the q-phase fluid.

Momentum Conservation Equation:

$$\frac{\partial}{\partial t}\left(\rho \vec{v}_q\right) + \nabla\left(\rho \vec{v}_q \vec{v}_q\right) = -\nabla p + \nabla \cdot [\mu \cdot (\nabla \vec{v}_q + \nabla \vec{v}_q^{\,T})] + \rho \vec{g} \tag{3}$$

$$\rho = \sum_{q=1}^{n} \alpha_q \rho_q \tag{4}$$

$$\mu = \sum_{q=1}^{n} \alpha_q \mu_q \tag{5}$$

It is in continuality, p is the internal pressure of the fluid, μ_q is the viscosity of q-phase, and $\vec{g}$ is the gravitational acceleration.

3.2. Numerical Simulation

3.2.1. The grid Division of the Calculated Region

The structure of the bionic flow path is a centrally symmetric three-dimensional model. To save computing resources and improve computational efficiency, half of the model is calculated. The simplified 3D virtual model is imported into ICEM for grid division. A prism grid is established at the boundary layer to ensure the accurate transmission of oil - gas - water mixed fluid dynamics. Although there is a positive correlation between grid number and computational accuracy, the number of grids and the amount of computation are negatively correlated, so the number of grids divided should be within a reasonable range. By comparing the test results with the laboratory prototype, the grid number is determined to be between 1 million and 2.4 million to meet the corresponding calculation requirements. The grid of the computational region of the bionic flow path is shown in Fig 3.

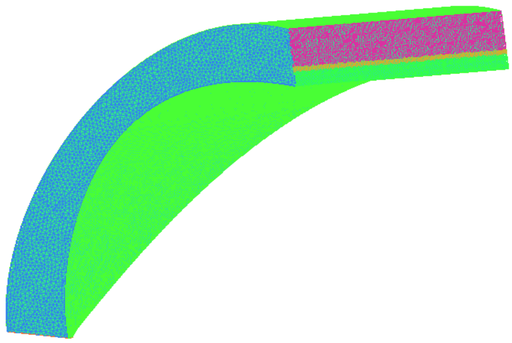


Figure 3. The grid of the computational region

3.2.2. Computational Model and Boundary Conditions

In real life, the flow of water in a river belongs to turbulent flow. Assume that the thickness of the oil slick is 5mm. In order to transfer the oil slick to the water separator as best as possible, the depth of draught at the lower end of the bionic channel is 20mm. The fluid medium in the bionic flow path is a three-phase mixture of kerosene, air and water. For the purpose of solving this problem accurately and conveniently, the least dense air is set as the main phase, and the oil and water are set as the secondary phase [9]. The specific properties of each phase are shown in Table 3.

Table 3.

The specific properties of each phase

The fluid medium	Air	Water	Oil
ρ/kg·m^{-3}	1.225	998.2	780
μ/kg/(m·s)	1.7894×10^{-5}	1.009×10^{-3}	2.4×10^{-3}

Import the divided grid model into the VOF three-phase model of CFD simulation software FLUENT for numerical calculation. The inlet of the bionic flow path is set to the velocity inlet, and the flow rate of water and oil is set to 0.6 m / s.

The solution is based on the pressure implicit transient solver. The viscous flow state is the RNG κ-ε (2epn) model. The coupling equations of pressure and velocities were solved with the SIMPLE algorithm. There is no slip on the solid wall surface. The convergence error is set to 10^{-3} and the maximum iteration number is 800.

3.2.3. Uniform Test Results

Table 4

The average values at outlet for experimental data

No.	The simulation data		Results of simulation test
	Flow rate of the mixture Q(m^3/s)	Volume fraction of the oil $\varphi_{(oil)}$	Flow rate of the oil $Q_{(oil)}$(m^3/s)
1	0.001263	0.1091	1.38E-04
2	0.003591	0.0852	3.06E-04
3	0.003034	0.1311	3.98E-04
4	0.003641	0.1037	3.78E-04
5	0.000776	0.0793	6.15E-05
6	0.003798	0.1170	4.44E-04
7	0.003944	0.1115	4.40E-04
8	0.015756	0.0267	4.21E-04
9	0.003657	0.1176	4.30E-04
10	0.005037	0.0754	3.80E-04
11	0.003257	0.1229	4.00E-04
12	0.003810	0.0945	3.60E-04
13	0.004143	0.0932	3.86E-04

Each set of test models was simulated in FLUENT for 6 hours or so. The model of bionic flow path corresponding to each data is obtained. The average flow rate of the mixture at the outlet and the average volume fraction of the oil at the outlet are shown in Table 4.

4. Optimization of Structural Parameters of Bionic Flow Path

The mathematical model of the flow of oil-gas-water mixed liquid in the bionic flow path is highly nonlinear. Therefore, the optimization of the structural parameters of the bionic flow path belongs to the nonlinear multivariable, and the objective function has the problem of strong nonlinear and complex constraints. It is a typical NP-hard problem. At present, intelligent optimization algorithms are used to solve such practical problems, such as artificial neural network (ANN), genetic algorithm (GA), ant colony algorithm, fuzzy algorithm, and so on. The idea of intelligent optimization algorithm stems from the operation principle of some inherent mechanism of biology or the producing principle of a natural phenomenon, which is a bionic breakthrough in theory. They have the characteristics of high parallelism, self-organization, self-learning and self-adaptation, which provide a new way to solve complex problems. In order to obtain the structural parameters of the bionic flow channel under the optimum transfer efficiency of the surface oil slick, the combined application of BP neural network and genetic algorithm is adopted [10-11].

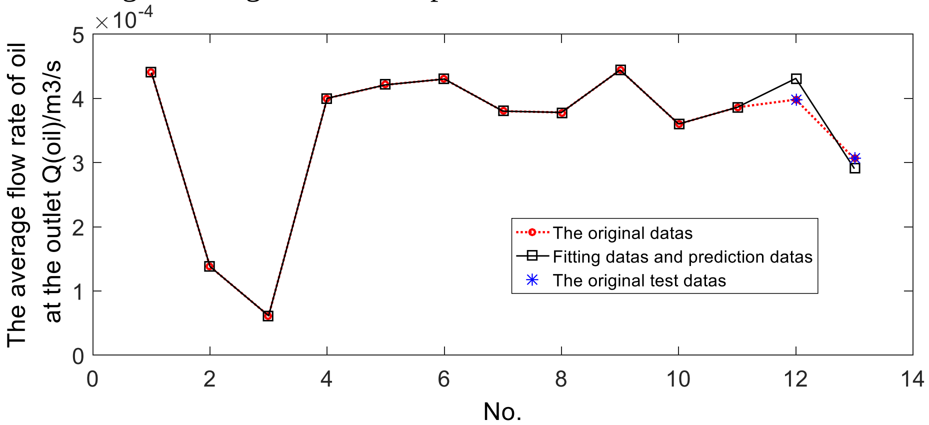


Fig. 4. The results of training and testing of ANN

BP neural network has strong nonlinear function fitting ability. In MATLAB, the first 11 sets of experimental input data and the corresponding output data were used to train the neural network with two topological structures with 33 hidden nodes. The latter two sets of experimental data matrices were used as the test set, and the training and test results were shown in Figure 4. Therefore, the trained BP neural network has better effect on the approximate fitting and prediction of the original test data.

BP neural network has good function approximation ability, but its optimization effect is poor, easy to get into local minimum. However, genetic algorithm has excellent global optimization ability. In this paper, the fitting function obtained by BP neural network approximation is used as the fitness function of genetic algorithm, and the fitness value calculation is carried out for each individual in the population, and then the calculation process of selection, crossover and mutation is calculated. And finally find the approximate maximum value of the average flow of oil at the outlet of the bionic flow path and the corresponding structural parameters of the corresponding bionic flow path.

With the MATLAB platform, get the parameters that meet the accuracy and time to solve after several simulation operations: the initial population size is 20, the crossover operator is 0.4, the mutation operator is 0.2, and the maximum iteration number is 100. The iterative process is shown in Fig. 5.

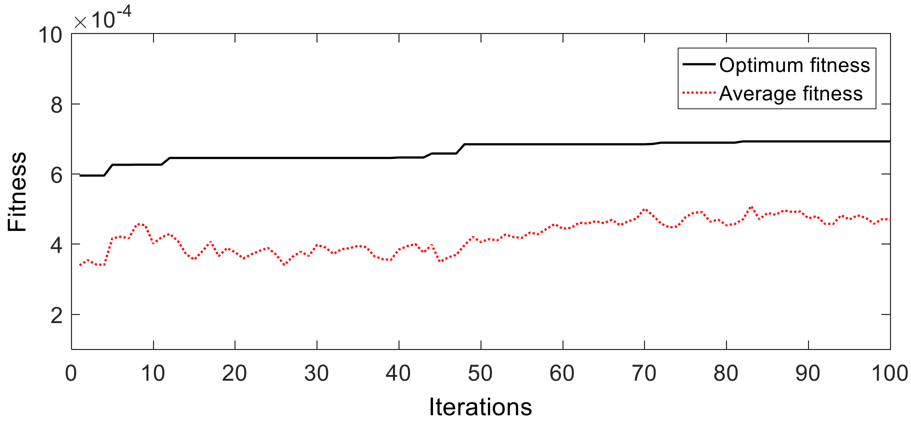


Fig. 5. The iterative process of GA

It can be seen from Fig. 5 that the algorithm is convergent after it is calculated by the iteration of 82 generations, and the optimal fitness is finally stable at 0.000693. That is, the average flow of the oil at the outlet of the bionic flow path is about 0.000693. And the corresponding structural parameters and optimization results of the bionic flow path after rounding are shown in Table 5.

It can be seen from Table 5 that the average flow rate of oil at the outlet of the bionic flow path after optimization of GA and ANN is greater than $1.49\times10^{-4}m^3/s$ before optimization.

Table 5.

Comparison table of optimization results of bionic flow path

Parameters	L_1 (mm)	L_2 (mm)	A (°)	B (°)	H_1 (mm)	H_2 (mm)	H_3 (mm)	$Q_{(oil)}$ (m^3/s)
The original model	270	780	40	-12	102	274	45	4.44e-4
The optimized model	435	705	37	-27	87	263	81	6.93e-4

5. Numerical Simulation of Optimization Model

5.1. External Characteristic

The same conditions and CFD numerical simulation method were used to verify the numerical simulation of the bionic flow path optimized by GA and ANN on the fluent platform. Thus, the iterative process of the average flow of the mixing fluid (Q) and the average volume fraction of the oil ($\varphi_{(oil)}$) at the outlet of the bionic flow path is obtained, in which the Q corresponds to the right Y coordinate, and $\varphi_{(oil)}$corresponds to the left Y coordinate, as shown in Fig. 6.

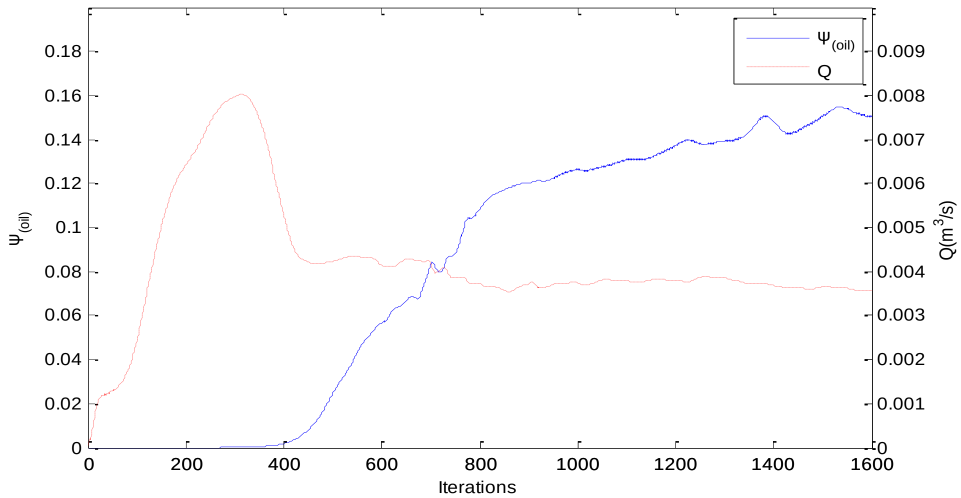


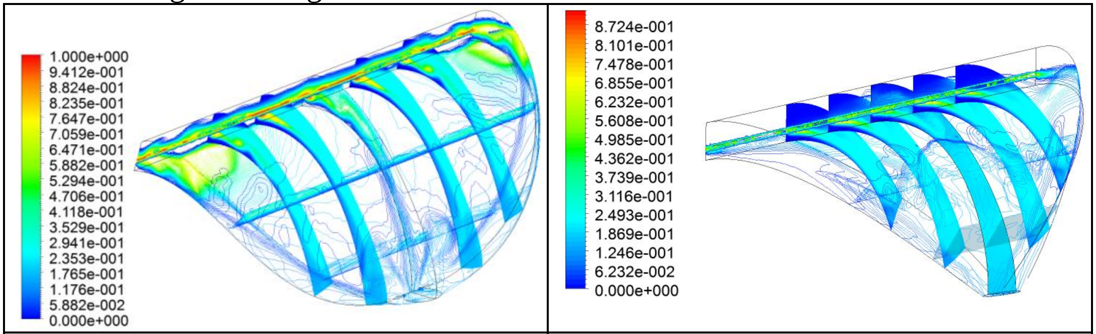
Fig. 6. External Characteristic of Optimization Model

As can be seen from Fig. 6, the average flow of the mixing fluid (Q) at the outlet of the optimized bionic flow path firstly increases, then decreases gradually, and finally tends to be stable. This is due to the first outflow from the bionic channel outlet is the internal air, and then with the oil and water mixture in the gravity and its own kinetic energy began to gradually flow out from the outlet, and eventually converged to $3.85\times10^{-3}m^3/s$. When the Q reaches the maximum (i.e., the oil-water mixed liquid starts to flow out of the outlet), the average volume fraction of the oil ($\varphi_{(oil)}$) begins to increase from 0 and eventually converges to 0.158 as the Q gradually stabilizes. The average flow rate of oil at the outlet of the bionic flow path is about stability in $6.083\times10^{-4}m^3/s$. This is very close to the result of optimization with the optimization algorithm. It is shown that GA and ANN optimization algorithms are feasible for the optimization of bionic flow path structure parameters.

5.2. Contrastive Analysis of Internal Flow in Bionic Flow Path

5.2.1. Distribution of Volume Fraction of Oil Slick in Bionic Flow Path

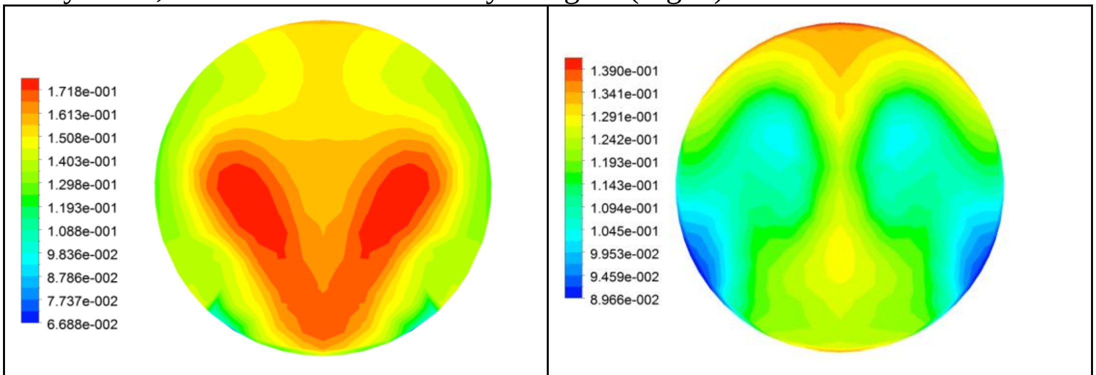
The volume fraction of oil slick is an important index for quantitative analysis of the oil content in the oil-gas-water three-phase mixed fluid in the bionic path. It clearly shows the spread of the oil slick inside the bionic runner, as shown in Fig. 7 and Fig. 8.



(a) The optimized model (b) The original model

Fig. 7. Contour of the volume fraction of the oil in the bionic flow path

The optimal model of the bionic flow path is larger than the original model; the absolute value of the rotation angle β of the x-axis of the reference coordinate system of the section 4 is larger than that of the original model. The angle between the entrance of the diversion channel of the bionic flow path and the horizontal surface is greater. More oil - water mixed liquid, which is accelerated by gravity and self kinetic energy, then collides with the posterior wall of the bionic flow channel (Fig. 7), resulting in a more complete mixing of the oil slick and water. In addition, the length L_1 of the section 2 of the optimized bionic flow path is larger than L1, which makes the middle of the bionic flow path more spacious. Therefore, the collision between the oil water mixture and the posterior wall of the bionic flow path is more sufficient. It also makes the oil slick and water mix more fully. Thus, the oil removal efficiency is higher (Fig. 8).

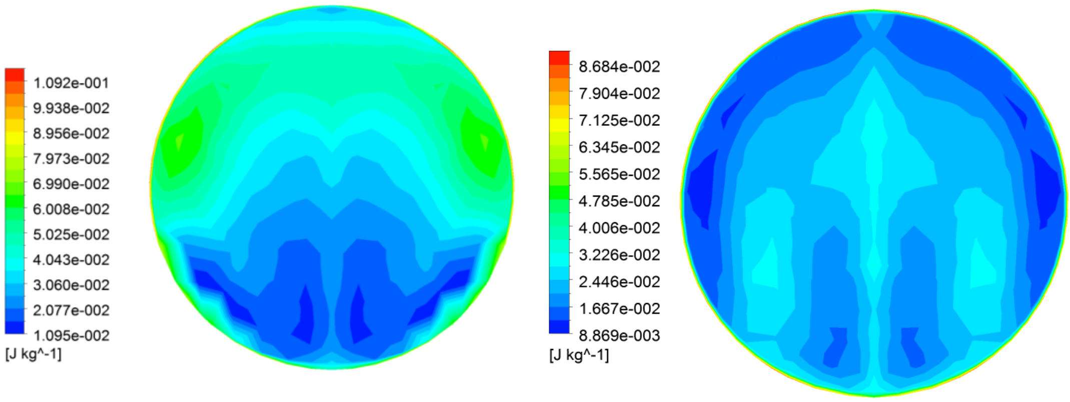


(a) The optimized model (b) The original model

Fig. 8. Contour of the volume fraction of the oil at the outlet of the bionic flow path

5.2.2 Distribution of Turbulent Kinetic Energy in Bionic Flow Path

Turbulent kinetic energy is not only an important index to measure the degree of fluid turbulence, but also a standard to evaluate the oil content in the oil-water mixed liquid flowing into the pump. It is also an index that cannot be ignored for quantitatively evaluating the performance of the end transfer device in a thin oil slick. Fig. 9 is a contrast contour of the turbulent kinetic energy at the outlet of the bionic flow path of the optimized model and the original model. It can be seen that the optimization model has more obvious turbulence than the original model of the bionic flow path at the outlet. It shows that the oil and water in the optimized bionic flow path can be mixed more fully. In this way, a much larger volume of lighter oil is suspended in the water, which is then removed by sewage pumps outside the channel.



(a) The optimized model (b) The original model

Figure 9. Contour of the turbulent kinetic energy at the outlet of the bionic flow path

6. Conclusion

(1) The experimental scheme of the structural parameters of 13 groups of bionic flow path was designed by uniform design experimentation method. The FLUENT platform was used to simulate the CFD full flow field in the flow of oil - gas - water mixture in the bionic flow path. On this basis, the optimal structure of the bionic flow path is obtained by using GA & ANN optimization algorithm. The average flow rate of the optimized bionic flow path is $1.49\times10^{-4}m^3/s$ higher than that before the optimization. This illustrates the superiority of the optimization method.

(2) The transfer efficiency of the bionic flow path is $|\beta|$ closely related to the rotation angle β of the x-axis of the reference coordinate system of section 4 and the length L_1 of section 2. Within a certain range, the greater the and L_1, the

more efficient the oil slick and water can be mixed, and hence the higher transfer efficiency of the oil slick.

(3) Turbulent kinetic energy is an important quantitative index of the efficiency of transferring oil slick in a bionic flow path. The greater the turbulent kinetic energy, the higher the oil transfer efficiency.

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