Analysis of the Influence of Pit Unit Arrangement on the Drag Reduction Performance of Fish-scale Pits

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Abstract. Apply Computational Fluid Dynamics (CFD) method to calculate the drag reduction effect of fish-scale pits with different arrangements under the same conditions. Through the analysis of wall shear stress, wall turbulence energy and axial velocity cloud diagram and velocity vector. It was found that the fish-scale pits can effectively reduce the shear stress and turbulent flow energy on the wall. At the same time, it was found that the bottom of the fish-scale pits formed tiny vortices flowing in the opposite direction. The "vortex cushion effect" is combined with the "pushing effect" caused by the friction generated by the bottom vortex, thereby reducing the friction. The research results show that the rhombus arrangement 2 can arrange a denser pit unit in the effective area to achieve a better drag reduction effect, and its drag reduction rate reaches 6.05%.

1. Introduction
After hundreds of millions of years of evolution, the creatures on earth have gradually developed the ability to adapt to the environment. Among them, many unique structures have become the direction of our science and technology development and learning [1, 2, 3]. For example, there are various grooves on the scale shield of the shark skin [4, 5]. After studying the grooves on the shark skin, Walsh[6] found that the downstream groove surface can optimize the shark swimming. In the research process of the relevant personnel using various forms of non-smooth surfaces to achieve drag reduction [7], they did not consider the influence of the arrangement order of the fish-scale pit non-smooth unit bodies on the drag reduction performance. Therefore, this paper chooses the Realizable (realizable) k-ε turbulence model computational fluid dynamics method, mainly to carry out the research on the drag reduction performance and the drag reduction mechanism of the fish-scale pit non-smooth surface with different pit unit arrangements.

2. Numerical simulation of non-smooth surface

2.1. Establishment of calculation model
The fish-scale pit is based on the ordinary spherical pit with the deepest point of the pit moving back a certain distance along the downstream direction. The computational domain model used in this paper is established by Catia. As shown in Figure 1, the upper surface is smooth and the lower surface is non-smooth, because the drag reduction effect of the pit-type non-smooth unit body only works in the boundary layer. In order to ensure that the incoming flow can fully develop, the width of the model is set to 10mm; the length is set to 30mm; at the same time, to avoid mutual interference between the upper
and lower surface flow fields, the height of the model is set to 10mm. The non-smooth surface is composed of non-smooth units of fish-scale pits and the spaces between them.

Existing studies have shown that placing non-smooth unit bodies in the boundary layer can effectively reduce the intensity of turbulent bursts, thereby reducing the loss of turbulent kinetic energy and achieving drag reduction effects. Therefore, the selection of the depth of the non-smooth surface of the scale-shaped pit is particularly important. For this reason, we control the depth $h$ of the scale-shaped pit within the minimum boundary layer. The thickness calculation formula of the boundary layer $\delta$ [8] is:

$$\delta = 0.37l/Re(l)^{1/5}$$  \hspace{1cm} (1)

$$Re(l) = Vl/\nu$$ \hspace{1cm} (2)

In the above formula, $l$ is the length of the plate, $Re(l)$ is the Reynolds number at $l$, $V$ is the incoming flow velocity, and $\nu$ is the kinematic viscosity coefficient of the fluid. It is calculated that the minimum boundary layer thickness at the location of the pits is 0.55mm. To ensure that the pit features are significant and considering that the pit depth is less than the minimum boundary layer thickness, this paper chooses $h$ to be 0.4mm.

### 2.2. Meshing and solving

The quality of mesh replacement will affect the accuracy and calculation time of the calculation result. In order to take into account the calculation accuracy and calculation time at the same time, the method of defining the size function is used to densify the surface of the fish-scale pit. The grid is sparse in the part far away from the pit. There are approximately 1210,000 grids and 510,000 nodes in the computational domain of each scheme in this paper. Meanwhile, the grid quality distribution is mainly concentrated in 0.7, and the overall grid quality is very high, as shown in Figure 2.

### 3. Calculate the simulation results

When an object is subjected to an external force, an internal force will be generated inside the object to resist the deformation of the external force. The internal force generated within the object is called shear stress. The result obtained by integrating the wall shear stress on the effective area of the entire wall is the viscous friction resistance of the wall [9]. The formula is:

$$F_f = \int \tau dA = \sum_{i=1}^{n} \tau_i |A_i|$$ \hspace{1cm} (3)
Research at this stage shows that frictional resistance is the main resistance to non-smooth surfaces in drag reduction applications. From the calculation results in the table below, it can be seen that by comparing with the smooth surface, the non-smooth surface of fish-scale pits can effectively reduce the viscous friction resistance of the calculation model. Based on the calculation results in the table, we can judge the diamond arrangement The drag reduction effect of 2 is the best, the drag reduction rate $\eta$ reaches 6.05%, followed by the rectangular arrangement, and the diamond arrangement 1 has the worst drag reduction effect. The calculation method of $\eta$ is as follows:

$$\eta = \frac{(F_{f2} - F_{f1})}{F_{f2}} \times 100\%$$  \hspace{1cm} (4)

In the formula, $F_{f1}$ is the viscous friction resistance of the flat plate model with fish-scale non-smooth surface; $F_{f2}$ is the viscous friction resistance of the flat plate model with smooth surface. The calculation results are shown in Table 1

| Pit arrangement          | Viscous friction resistance | Total drag reduction rate/% |
|--------------------------|-----------------------------|----------------------------|
| No pits                  | 2.842E-4                    | /                          |
| Rectangular arrangement  | 2.723E-4                    | 4.19                       |
| Diamond arrangement 1    | 2.743E-4                    | 3.65                       |
| Diamond arrangement 2    | 2.670E-4                    | 6.05                       |

4. Analysis of drag reduction mechanism

4.1. Wall shear stress analysis

Figure 3 shows the comparison of wall shear stress between a smooth plane and a non-smooth plane with different pit arrangement sequences. The flow direction is from left to right. From the overall distribution point of view, the wall shear stress of the non-smooth plane in various arrangement orders is less than the wall shear stress of the smooth plane. At the same time, it can be observed from the distribution in the figure that the difference in the shear stress at the entrance is not large, but when encountering The wall shear stress begins to change when the microstructure of the fish-scale pits. It can be seen from the figure that the shear stress at the fish-scale pits is significantly smaller than the surrounding area, indicating that the location where the fish-scale pits are arranged has a significant drag reduction effect, and it can be observed that the shear stress on the wall varies with the number of pit unit arrays.
4.2. Analysis of wall turbulence energy

Turbulent kinetic energy characterizes the length of turbulent pulsation, that is, the frequency of fluid energy exchange and conversion. The greater the turbulent kinetic energy, the greater the energy loss. Figure 4 shows the comparison of turbulent kinetic energy between a smooth plane and a non-smooth plane with different pit arrangement orders. The flow direction is from left to right. It can be seen from the figure that the turbulent kinetic energy at the entrance of the four models is basically the same, but in When encountering the microstructure of fish-scale pits, the turbulent kinetic energy is significantly reduced, and the turbulent kinetic energy in the surrounding area is also reduced at the same time, which greatly reduces the kinetic energy consumption near the wall, that is, the drag reduction effect is achieved.

Also in order to further analyze the influence of the fish-scale pit structure on the wall turbulent kinetic energy, we extract the wall turbulent kinetic energy along the central axis of the flow direction and draw the wall turbulent kinetic energy distribution curve. As shown in Figure 5, it can be observed
that in the smooth water domain at the front end of the calculation domain, the turbulent kinetic energy of the non-smooth surface and the smooth surface are basically the same. When the fluid passes through the fish-scale pit microstructure, the turbulent kinetic energy of the non-smooth surface shows a significant decrease.

Figure 5 Wall turbulence kinetic energy curve comparison diagram

4.3. **Velocity vector diagram analysis of pit interior**

In order to further observe the internal flow of the fish-scale pit, a vector diagram of its internal velocity is drawn along the section, as shown in Figure 6. By observing the velocity vector inside the fish-scale pit, it can be found that the reverse fluid in the velocity cloud diagram is actually a tiny vortex formed at the bottom of the pit. This reverse vortex is equivalent to a roller on a non-smooth surface, turning the sliding friction at the contact position into Rolling friction, because the rolling friction is smaller than the sliding friction under the same conditions, the tiny vortex formed inside the fish-scale pit effectively reduces the viscous friction resistance of the fluid when the fluid passes through the wall. Compared with the sliding friction of the fluid on a smooth surface, a non-smooth surface The rolling friction on the surface is more conducive to the passage of fluid. We usually call this phenomenon the "vortex cushion effect".

Figure 6 Vector view of the interior of a fish scale pit
5. In Conclusion
In this paper, numerical simulation calculations of fish-scale pits arranged in different arrangements are carried out. The fish-scale pit structure not only reduces its own wall shear stress and turbulent kinetic energy, but also reduces the turbulent kinetic energy in the surrounding area and reduces energy loss to achieve drag reduction. Studies have shown that the non-smooth surface structure of fish-scale pits can generate tiny vortices inside the pits, forming a "vortex cushion effect", which converts the sliding friction between the gas and the solid into rolling friction, combined with the formation of the bottom of the vortex. The reverse friction force produces a "pushing effect" on the fluid, and the combined action of the two effects effectively reduces the frictional resistance.

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