World Scientific Research Journal Volume 7 Issue 3, 2021
ISSN: 2472-3703 DOI: 10.6911/WSRJ.202103_7(3).0048

Research on Antifouling Mechanism of Patterned Surface based on 3D Numerical Simulation

Hongyue Yang[1, a, *]

[1]Department of Power Engineering, North China Electric Power University, Baoding 071003, China

[a]anngyang_ncepu@163.com

Abstract

The anti-fouling performance of the patterned surface has been widely verified, but the anti-fouling mechanism still needs to be further explored. The microfluidic properties are an important reference factor for evaluating the anti-fouling performance of patterned surfaces. The research investigated the influence and distribution of high-speed flow near the surface, wall shear stress and strain rate, and compared the difference between patterned surfaces and smooth surface. These effects may affect the movement of microorganisms in the fluid and reduce the sedimentation.

Keywords

Microstructured surface; Numerical simulation; Antifouling; Flow characteristics.

1. INTRODUCTION

Marine anti-pollution is a difficult problem in marine development, and microstructure surface antifouling technology has become a research hotspot. In nature, sharks, crabs, starfish and shells have very precise microstructures. Their hydrophobicity and self-cleaning properties have broad prospects in antifouling research.

It is believed that the characterization of patterned surfaces based on anti-fouling effectiveness is complex. Scardino et al. put forward the "attachment contact theory", and considered that the sufficient number of contact points between fouling organisms and attached surface was the premise of successful attachment of fouling organisms [1].

On this basis, Schumacher et al. proposed four types of microstructural surfaces with 2-mm spacing and 3-mm height were experimentally studied. Patterns designed included geometric features of 2-mm-wide ribs of various lengths, 2-mm-diameter circular pillars, 2-mm-wide continuous ridges, and 10-mm equilateral triangles. These surfaces were found to correspondingly reduce spore settlement by 77%, 58%, 36%, and 31%, respectively. After that, they established the concept of engineering roughness index (ERI) to predict the spore attachment of Ulva lactuca. ERI was determined as the dimensionless ratio of Wenzel roughness factor (r), depressed surface fraction (fD) and degree of freedom for movement (df) [2]. Long et al. established the ERI II model, replacing df in the ERI model with n (the number of distinct features in the surface design), introducing φs (the area fraction of the feature tops) to the improved model, and using natural logarithm to predict the spore attachment density of green algae [3] .

Neither of the ERI models considered the wettability, mechanical properties and microbial characteristic size of materials, and could only effectively predict the attachment density of Ulva lactuca spores, but could not predict the attachment density of other microorganisms. Built on this, the fluid Reynolds number (Re) and the sensitivity factor m of microorganisms to the surface were taken into account by Magin et al [4]. However, the sensitivity factor m only unified the prediction models of different organisms into one formula by setting the proportional coefficient. Decker et al.meshed the microstructured surface and added the interface free energy on the basis of the two ERI models to establish the SEA model [5]. The limitation of nano-force gradients model is that the microorganism can only attach to the protruding area of microstructure and needs multiple attachment points. SEA model can predict well the adhesion of several microorganisms, but some prediction results are inconsistent with the nano-force gradients model.

Halder et al. used numerical simulation to study the antifouling effect of the round-hole microstructured surface from the macro and micro levels, focusing on the velocity and shear stress distribution of the flow field, and added a single E. coli simplified model (bacteria simplified as two connected cylinders) into the flow field [6]. The simulation results showed that the change of wall shear stress had a great impact on the initial attachment of microorganisms.

In recent years, many scholars have analyzed the distribution of flow velocity and shear stress through CFD simulation, and explored the antifouling and antibacterial properties of materials or membranes with micronano structure. Our study investigated the effects and distribution of high-speed flow, wall shear stress and stress gradient near the surface of microstructures.

2. MATHEMATICAL PHYSICAL MODEL

In this article, we simulated three-dimensional laminar fluid flow in the channel, and the inlet velocity was u0. As shown in Figure 1, the length, height and width of the channel were respectively Lx=300μm, Ly=40μm,Lz=80μm. The protrusion between adjacent pits was a=2μm. In order to eliminate the influence of the inlet and outlet sections on the fluid state, a certain length of smooth surface was set up at the inlet and outlet sections of the channel. The microbial model was simplified as a sphere with a radius of r, and the distance between the bottom of the microorganism and the surface of microstructure was d. Microbes move downstream in the microchannel.

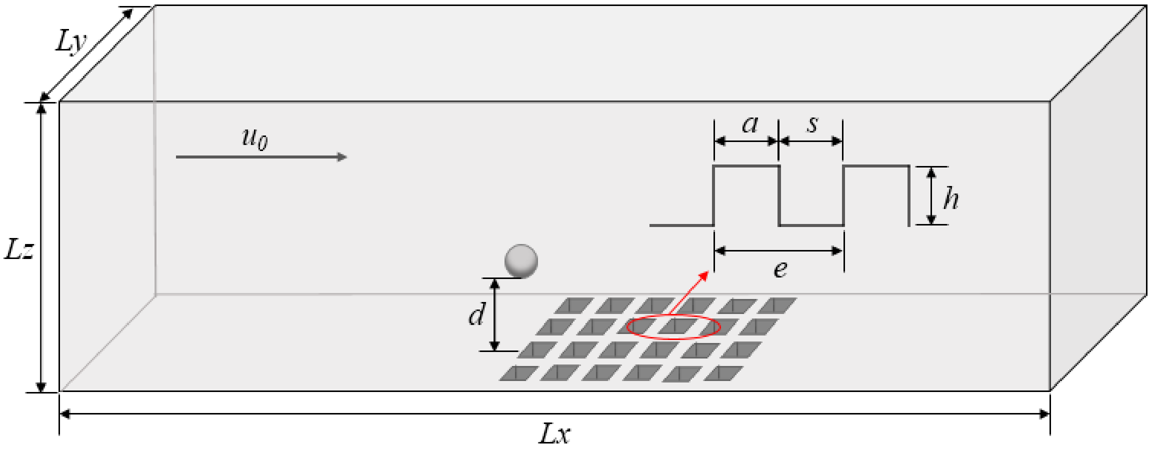


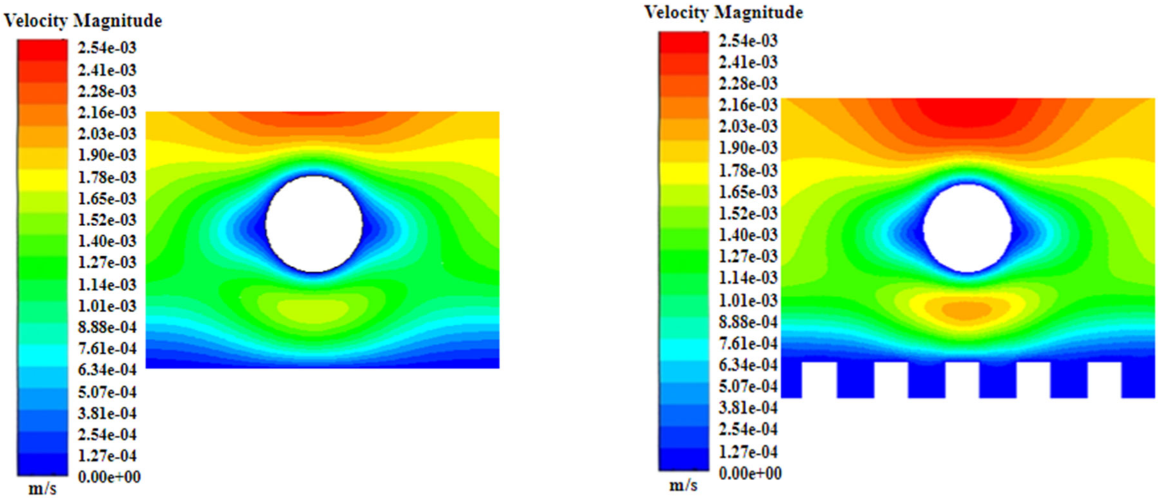
Figure 1. Three-dimensional model of the microstructured surface with micropits

Unstructured and structured meshes were employed around the microorganisms and the microstructure, respectively. Considering the accuracy of numerical simulations and the calculation time, the total grid number was determined to be 1.9 million.

3. SIMULATION RESULTS AND DISCUSSION

3.1. The Effect of Moving Microorganisms of Flow Velocity

Microorganisms on patterned surfaces experience a complex microhydrodynamic environment, which includes differential strain rates, fluctuating velocity and wall shear distribution that develops by the microstructured surfaces. Figure 2 shows the fluid velocity distribution of microorganisms at the surface of the microstructure and plane surface. As shown in Figure 2, when the fluid flow around the intermediate occurs by microorganisms and microstructure, the velocity above microstructured surface was significantly higher than the plain surface. The higher velocity enables microorganisms to pass through the surface quickly, which means reducing sedimentation and adhesion.



(a) (b)

Figure 2. Fluid velocity distribution of plane surface and microstructured surface.

3.2. The Effect of Moving Microorganisms of Wall Shear Stress

Wall shear stress can reduce the adhesion of microorganism, or make them be cutted off after they attach the surface. The protrusion between two adjacent pits was called microridge. Figure 3 presents the wall shear stress distribution profile on the microstructured surface. The microbe is on the micro-ridge B, moving in the x-axes from left to right. Figure 3 shows the shear stress of micro-ridges A and B in the direction of microorganism movement is significantly lower than that of micro-ridges at the same position in the y-direction. The shear stress of micro-ridge C is also lower than other adjacent ones. Table 1 shows the different micro-ridge shear stress values. It can be seen that the shear stress of C in front of the microorganism is higher than that of A and B. Therefore, the presence and proximity of microorganism deduces the effect of wall shear stress.

Table 1. Shear stress of adjacent micro-ridges in the direction of microbial movement

Shear stress	A	B	C
$\overline{\tau}$ (Pa)	0.651	0.678	1.884
τ_{max} (Pa)	1.059	1.233	2.768
τ_{min} (Pa)	0.902	0.951	2.458

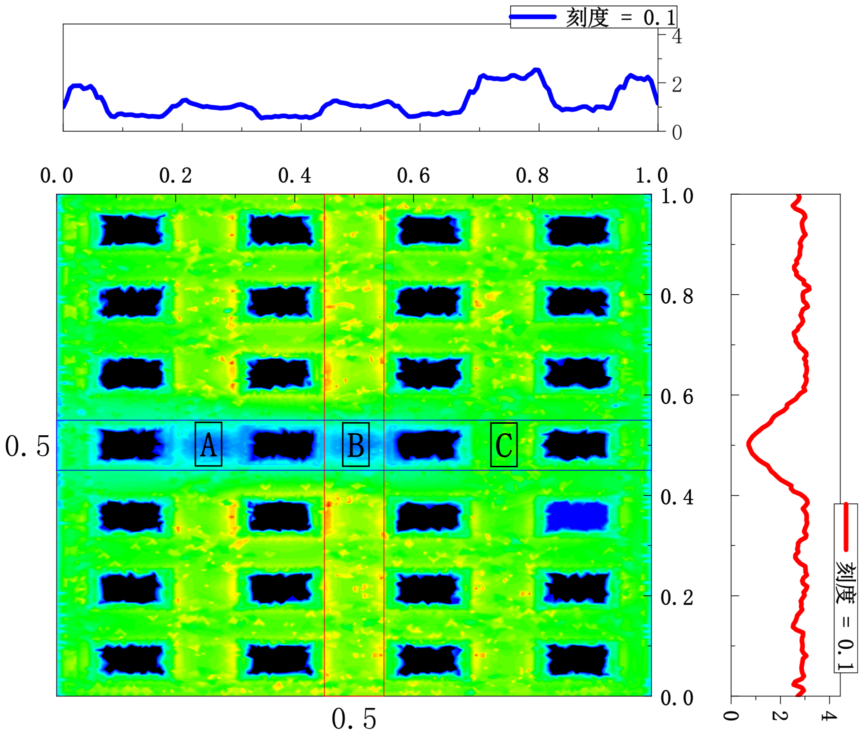
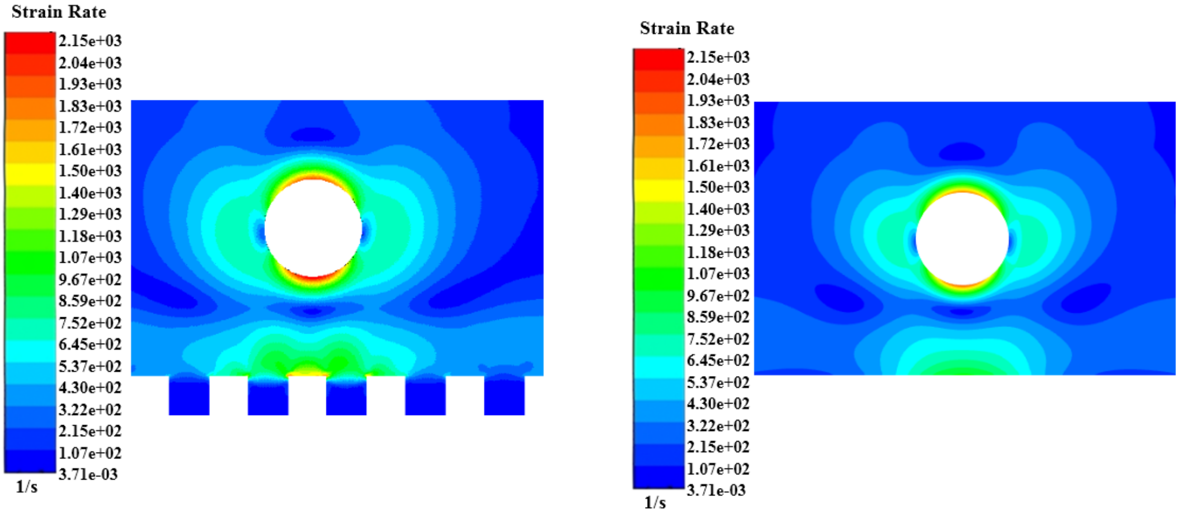


Figure 3. Wall shear stress distribution profile on microstructured surface

3.3. The Effect of Moving Microorganisms of Strain Rate

Figure 4 shows the fluid deformation rate experienced by microorganisms on their body surface when they are at the same height on their surface. There are obvious continuous microfluidic disturbances near the pattern surface. When the microorganisms move at the same height on the plain surface and the microstructured surface, the fluid strain rates of different strengths that the microorganisms experience on their body surface. Therefore, microorganisms can feel the difference in fluid changes, and cause changes in the movement process of the organism, and it is not easy to settle in areas with severe changes.



(a) (b)

Figure 4. Strain rate distribution of plain surface and microstructured surface. White cicle presents moving microorganism. (a) Strain rate of plain surface distribution; (b) Strain rate of microstructured surface (h=2μm, s=2μm)

4. CONCLUSIONS

In this paper, a rectangular micro-pit surface containing moving microorganism is established. The movement of spherical algae with a diameter of 3μm in the near-wall area is simulated by CFD. By investigating the distribution of flow velocity, wall shear stress and strain rate above the microstrutured surface, and analyzing the influence on the attachment of microorganisms, the following conclusions are obtained:

The fluid velocity on the surface of the microstructure is higher than that of the smooth surface, and exhibits periodic fluctuations (the change of the smooth surface velocity is almost zero). The simulation results show that the patterned surface shear stress is greatly affected by microorganisms, and a low shear stress area is formed around it. Therefore, when microorganisms move in the near-wall area, the effect of shear stress is overestimated.

The strain rate can intuitively show the interaction between fluid and microorganisms. Fluid changes are perceived by microorganisms through different pressures acting on the surface of the microorganism's body. That makes the patterned surface not suitable to settle.

ACKNOWLEDGMENTS

This work was financially supported by Fundamental Research Funds for the Central Universities of Ministry of Education of China. (Grant No. 2015MS105)

REFERENCES

[1] A J Scardino, E Harvey, N R De . Testing attachment point theory: Diatom attachment on microtextured polyimide biomimics. Biofouling. (2006) 55-60.

[2] J.F Schumacher, M.L Carman, T.G Estes, A.W.Feinberg, L.H. Wilson, M.E. Callow, J.A. Callow, J.A. Finlay, A.B. Brennan. Engineered antifouling microtopographies-effect of feature size, geometry, and roughness on settlement of zoospores of the green alga ulva. Biofouling (2007) 55–62.

[3] C.J. Long, J.F. Schumacher, P.A.C Robinson, J.A Finlay,.; M.E. Callow, J.A Callow, A.B Brennan. A model that predicts the attachment behavior of ulva linza zoospores on surface topography. Biofouling (2010) 411-419.

[4] C.M. Magin, C.J Long, S.P Cooper, L.K Ista, G.P Lopez, A.B. Brennan. Engineered antifouling microtopographies: the role of Reynolds number in a model that predicts attachment of zoospores of ulva and cells of cobetia marina. Biofouling (2010) 719-727.

[5] J.T.Decker, C.M Kirschner, C.J. Long, J.A Finlay, M.E. Callow, J.A Callow, A.B. Brennan. Engineered Antifouling Microtopographies: An Energetic Model That Predicts Cell Attachment. Langmuir (2013) 13023–13030.

[6] P Halder, M Nasabi, N Jayasuriya, J Shimeta, M Deighton, S Bhattacharya, A Mitchell, M.A Bhuiyan. An assessment of the dynamic stability of microorganisms on patterned surfaces in relation to biofouling control. Biofouling (2014) 695–707.