A Numerical Assessment of the Efficacy of a Topography Design with Increasing Gradient Complexity for Filtering Biofouling Material through the Membrane Module of a Water Treatment System

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Abstract. Biofouling can also be defined as the micro- / macro- organisms stuck on the surface that has been submerged in water. This is normally found in marine industry and water treatment industry. There are 3 ways of antifouling where the 3\textsuperscript{rd} method surface modification was the main point to be focused on. Surface modification has high potential for antifouling performance and is not harmful to the ecosystem. In this research study was to find out the efficacy of antifouling performance with increasing the gradient complexity. The 2 models used were smooth topography and circular topography and have been manipulated and simulated with WorkBench 2020, Computational Fluid Dynamic (CFD). The results were simulated with the correct meshed and models. The simulated results were converged and 2 hydrodynamic variables; velocity and wall shear were used to check the efficacy of antifouling performance.

1. Introduction

Biofouling is also known as the gradual process of micro- / macro- organisms that grow or stick on the surface that has been submerged in water. When biofouling is found on the submerge surface, the surface metal would probably corroded / rusted, and the efficiency of the moving parts will dramatically decrease, for example with the present of biofouling, the speed of marine will decrease and will not have the expected performance on mobility, this will lead to high consumption of fuel. Besides that, there are also industry that biofouling brings trouble to which is on the water treatment system were located on the porous surface of the filtration membrane for example nanofiltration and reverse osmosis which increase the pressure and the support will be damaged, this will lead to high cost since require more energy and maintenance [1].

Biofouling is a natural phenomenon that cannot be avoided but there are some of the ways that have been used to encounter the early stage of biofouling. The most early antifouling method which is also very effective towards biofouling is biocidal antifouling coating. This coating can efficiently kill the fouling micro- or macro- organism when there is contact with the coating. As biocidal antifouling coatings are highly efficient on antifouling but still not sustainable to be used due to the side effect. This method has high toxicity which is very harmful to aquatic lives. Therefore, the researchers find more ways of antifouling to replace this biocidal antifouling coating. Biocidal antifouling coating this kind of high efficient antifouling method has then been banned to protect the global and aquatic life [2].
After coating has been banned, scientists and researchers came out with another method which have the function of antifouling and was harmless to aquatic life, and this method is called foul-release coatings [3]. This foul-release coating method does not kill micro- or macro-organisms, but this method has the function of reflecting the micro- or macro-organism also known as detachment from the surface [4]. Unfortunately, this method is not as efficient by comparison to biocidal antifouling coating [2]. The micro- or macro-organism will still be stuck on the submerged surface [2].

While foul-release coating methods were not harmful to aquatic life, but the biofouling functionality was low efficiency and unstable, the researchers then came out with the third method of antifouling which is called surface modification. Surface modification is non-toxic and has a foul-resistant antifouling function with the presence of topographies on the surface [5]. This third method, surface modification topographies have been commonly used in the recent decades since this is a potential and non-toxic method to the ecosystem [6]. This surface modification topographies have a lot of potential and promising results compared to both of the previous methods; therefore, further research has been done and ongoing for this new method [6]. Surface modification topographies antifouling function is based on the topography geometry pattern on the surface where is inspired by biomimicry, the nature topographies such as micro-riblets (surface of shark skin), honeycomb pattern (bee’s nest shape), lotus leaves, pilot whale skin and more has been found as the potential surface topographies geometry [7]. There is also inspiration that based on non-biomimicry such as, prisms, pyramid, circular, rectangular, and more have also been researched as potential antifouling [7]. All these biomimicry and non-biomimicry topographies have high microfluidic condition which lead to high antifouling if this was implement on the submerge surface such as membrane filtration on water treatment system and marine industry surface [8]. This will be listed in Tab. 1 to have a clear view of both biomimicry and non-biomimicry.

Table 1. Inspiration of biomimicry and non-biomimicry surface modification topographies

| Biomimicry          | Non-biomimicry |
|---------------------|----------------|
| Micro-riblets       | Prisms         |
| Honeycomb pattern   | Pyramid        |
| Pilot Whale Skin    | Circular       |
| Lotus Leaves        | Rectangular    |

These are some of the examples for inspiration of biomimicry and non-biomimicry which there are more examples has been research but there are not much of research made for increasing the gradient complexity and check the efficacy have efficiency of the antifouling.

In surface modification method, the geometry sizing was a very important variables that will influence the performance of antifouling. By comparing the topographies geometry, the geometry size is more important by selecting the correct sizes of geometry size [9]. In general research paper, there will be 2 different topographies size will be use to manipulate in surface modification method which are macro and micro where the scale of these 2 sizes are in the range of 1 to 100 in mm/μm [10]. There was a research study stating macro-size were used for antifouling where macro- size geometry can antifoul macro- and micro-organisms [12]. There are another research study by Aldred et al. conducted with the settlement of cyprids which it is in the width of micro topographies in the range of 1 to 256 μm and the result shows the antifouling performance is high efficient [11]. Based on the second research study results, it provides the example and result to prove that the micro-size topography has high efficacy therefore, in this research project will be conducted with micro-size topography. Besides that, in general and second research papers have mentioned that micro-size topography are suitable to be applied to have better performance in antifouling and this shows that micro-size topography is better than macro- size topography [13].

Recent years, there were two ways for the researchers to get the desired results. These 2 ways were experimental and numerical [14,15]. For getting high efficacy of antifouling performance with micro-size topography and different gradient complexity of geometry for filtration membrane surface in water treatment system with an experimental result will require a lot of knowledge, time and cost where
Numerical way will be more suitable to be approached. Nevertheless, numerical results with the correct application of boundary conditions will give more reliable results compared to experimental results. In addition, researchers have been implementing and relying on numerical results and this is because the researchers can change the variables and control the process in any way the researcher want the condition to be to provide reliable results with the support of data. Thus, in this project research will be done with the help of numerical ways and the simulation software will be using Computational Fluid Dynamics (CFD) 2020 simulations and SolidWorks 2018. In this project research was mainly focusing on the efficacy of the antifouling when increasing the gradient complexity of filtration membrane in a water treatment system. Therefore, the further numerical investigations were required to validate the efficacy of the research outcome.

2. **Research Methodology**

The 3 methods which were biocidal antifouling coating, foul release coating and surface modification were mentioned in introduction and the 3rd method, surface modification was used in this research project and with the help of SolidWorks 2018 and ANSYS WorkBench 2020 to get the results. This two software was used to model the fluid geometry and simulate the completed model and get desire results. There were some of the variables that need to implement in the modelling and conditions need to be stated clearly for simulating the pre- and post-processing to get the correct results.

2.1 **Geometry Modelling**

There were 2 models that have been completed with sketch and extrude with SolidWorks 2018. These 2 models are plain surface (smooth surface) and another one with circular topography. The dimension for domain (fluid sections) has been set with the volume of $8\text{mm} \times 2\text{mm} \times 25\text{mm}$ rectangular shapes and from inlet to the circular surface topography is $15\text{mm}$ as shown in Fig. 1. For the circular surface topography have the size of $250\mu\text{m}$ which is in the range of $1 – 256\mu\text{m}$, the depth of every circular surface topography is $250\mu\text{m}$ and the spacing between circular surface topography is $400\mu\text{m}$ as shown in Fig. 2. Fig. 1 and Fig. 2 are displayed as 3D modelling. Fig. 1 displays the isometric view of the circular topography with the domain. Fig. 2 display the side view with zoom in to show the dimension of the circular topography.
Figure 1. Isometric view of circular surface topography

Figure 2. 3D modelling of one circular surface topography

2.2. **Mesh Generation**

As both models were successfully modelled and imported into 2 different files of ANSYS WorkBench fluid fluent (flow) also known as Computational Fluid Dynamics (CFD) geometry section. In the mesh section, tetrahedral was applied to these 2 models and this is because these models are not considered as simple shapes due to the complexity of the topographies. Besides that, there was a refinement mesh for the topographies (circular & smooth) area, since these are the sections that need to be focused on where this could save up the time with having accurate results. There was also inflation applied to these with layer 7 thickness. This setup was to ensure that in the end the manipulation on having the result can be converged and have the data for the body meshed in domain, edge sizing at the domain edges (12 edges) and face sizing at the face of the topography set. This has been done with 2 different set of numbers as shown in Tab. 2. The reason these 2 different sets of data have been applied was because to reduce the simulation time and the results are still reliable and accurate.
Table 2. Smooth topography and circular topography mesh details

| Topography | Mesh method  | Body Mesh (mm) | Edge Sizing (mm) | Face Sizing (mm) |
|------------|-------------|----------------|------------------|------------------|
| Smooth     | Tetrahedron | 0.5            | 0.01             | 0.01             |
|            |             | 0.6            | 0.02             | 0.02             |
| Circular   | Tetrahedron | 0.5            | 0.01             | 0.01             |
|            |             | 0.6            | 0.02             | 0.02             |

The reason why 0.6 mm body mesh, 0.02 mm edge sizing and 0.02 mm face sizing has been applied and chosen was because the simulation run faster, and results were accurate and reliable. In Fig. 3 shows the circular topography body mesh of 0.6 mm edge sizing and face sizing of 0.02 mm.

Figure 3. Mesh of circular topography

Fig. 3 clearly shown that the edge of the rectangular and circular topography has been fine mesh comparing the mesh on the fluid domain since the result was focusing more on the topography section compared to the fluid domain.

This project research was to find the efficacy of antifouling when the topography gradient complexity increases. Therefore, the settings for smooth and circular topographies have the same set up and compare the differences. Tab. 3 shows the different number of elements and nodes with the same mesh condition set on the 2 models.

Table 3. Number of element and nodes for smooth and circular topography

| Topography | Body Mesh (mm) | Edge Sizing (mm) | Body Sizing (mm) | No. of Element | No. of Nodes |
|------------|----------------|------------------|------------------|----------------|--------------|
| Smooth     | 0.6            | 0.02             | 0.02             | 2049156        | 409367       |
| Circular   |                |                  |                  | 2054405        | 437882       |

After the meshing is completed, name selection needs to be clearly set and this can be used in the pre-processing and post-processing. After setting the name selection and the specific section can be focused on having the result based on the surface. Name selection has been set and shown in Fig. 4.
2.3 Numerical Setup (Pre-Processing)

Before setting up any further pre-processing, the volume and orthogonal quality need to be checked and compared with the theoretical values. The smooth and circular topography will share the same theoretical conditions on checking the volume and orthogonal quality. Based on the theory, before any further steps taken, the minimum volume of any model (fluid) ensures all positive values. For mesh quality wise, this was important in getting converged results to obtain an accurate solution. The minimum orthogonal quality should be higher than 0.01 (theoretical value) and maximum aspect ratio cannot exceed 35 to have a better mesh quality. Tab. 4 stated the volume and orthogonal quality results.

**Table 4.** Minimum volume and mesh quality for smooth and circular topography

| Topography | Min. Volume (m) | Mesh Quality | | | |
|---|---|---|---|---|---|
| | | Min. Orthogonal Quality | Maximum Aspect Ratio | | |
| Smooth | 6.06E-17 | 5.42E-02 | 6.79E+01 | | |
| Circular | 6.43E-17 | 5.45E-02 | 7.55E+01 | | |

Based on Tab. 4, minimum volume of smooth and circular topography stated were both positive values where these values met the theoretical condition. For mesh quality, the minimum orthogonal quality value was more than 0.01 (theoretical value) and maximum aspect ratio is lower than 35 (theoretical value) after inflation conditions applied, where normally with inflation applied, the maximum aspect ratio will increase.

Since all the conditions met the theoretical conditions, these two models can proceed with the further step. This project research is mainly focus on the water flowing through filtration membrane in a water treatment system.
2.3.1 Governing equation.

Water flowing through a filtration membrane in water treatment system is normally found to be steady and incompressible flow. In this project research, the CFD simulations will be implementing continuity and Navier-Stoke equations to find the pressure and velocity fields. Since is the condition of water passing through filtration membrane to be steady, the implemented 2 equations can summarise as follows:

\[ \nabla \cdot \mathbf{v} = 0 \]  
\[ \rho \frac{\partial \mathbf{v}}{\partial t} = -\nabla P - \rho \mathbf{g} + \mu \nabla^2 \mathbf{v} \]  

Expanding the \( \mathbf{v} \) \( \mathbf{v} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k} \)

where \( u, v \) and \( w \) = velocity in x, y and z directions.

In CFD simulation, the viscous model was set to be laminar flow since laminar flow is the condition of steady and incompressible flow condition. The energy equation has also been turned on since considering the ambient temperature in the water treatment system and set it to be 25°C.

2.3.2 Initial and Boundary Condition.

Since this was a water treatment system that water passing through filtration membrane, the fluid under material model was set as water liquid, \( H_2O < l > \) which has the default properties of density: 998.2 \( \frac{kg}{m^3} \) and dynamic viscosity: 0.001003 \( \frac{kg}{ms} \). At the boundary condition of inlet will be set as mass-flow-inlet with the value of 0.001 \( \frac{kg}{s} \) and temperature of 298.15 \( K \). For outlet was set as pressure outlet condition and pressure value is 0 Pa. For the top surface, bottom surface and bottom topography walls, the condition set as no slip and stationary wall.

2.3.3 Data Acquisition (Post-Processing)

In this project research simulations of fluid flow, there are 2 hydrodynamic variables that need to be find which are velocity and wall shear. There were 3 different location lines has been stated on the topography of smooth surface and circular topography surface which are at the top, middle and bottom lines will be focused to check these 2 hydrodynamic variables. Fig. 5 clearly display the 3 different locations for smooth and circular topography.

\[ \text{Figure 5. Location set to find the 2 hydrodynamic variables: (A) smooth surface (B) circular surface topography with blue line (top line), yellow line (middle line), and purple line (bottom line)} \]

These 3 locations were at 0.25mm (top line), 0.125mm (middle line) and 0mm (bottom line) of the topography surface. The thickness for a smooth surface is to make the condition of the smooth surface to be like the circular topography surface. Smooth surface and circular topography surfaces have the same volume. These 2 model solutions have been converged and these models can proceed to further post processing steps on checking these 2 hydrodynamic variables.
3. Results and Discussion

Velocity and wall shear will be displayed and discussed. These 2 are the main hydrodynamic variables that need to be considered for finding the performance of antifouling on these 2 models: smooth surface topology and circular topology. All the numerical results from Ansys Workbench 2020 will be recorded and discussed.

3.1 Velocity

As mentioned in section 2.3.1 governing equation, the equation of \( \vec{V} = u\vec{i} + v\vec{j} + w\vec{k} \) can also be expressed as velocity u, v and w and magnitude \( \vec{i}, \vec{j}, \vec{k} \) which was for the direction of x, y and z. Biofouling will have a larger chance to grow if the velocity is as low as zero. Therefore, there will be comparisons for smooth and circular topography.

Since smooth and circular topography have the same inlet condition, the circular topography inlet contour has been used to show the inlet surface. Fig. 6 shows the inlet contour velocity condition of circular topography.

![Figure 6. Velocity at the inlet of circular topography with the inlet line](image)

The inlet line in Fig. 6 has been set. This inlet line was drawn at the y-axis from the top to the bottom of the inlet surface which is 2mm length. Observation from Fig. 6, the velocity near the edge of the inlet is \( 0 \text{ m/s} \). As the velocity in the midplane shows the maximum velocity which is \( 1.003E - 01 \text{ m/s} \). The colour changes from blue (near the edges) to red (midplane) of the inlet of the domain. Fig. 7 was the velocity graph based on the inlet line shown on Fig. 6 located on the inlet of the domain.
Figure 7. The inlet line velocity graph located at inlet domain of circular topography

From Fig. 7 the maximum which was at 1 mm also known as the red zone in Fig. 6. This shows that in the middle of the inlet has the lowest chance to have biofouling on the surface compared to the edges of the domain inlet.

Fig. 8 shows the graph of the smooth surface topography. This has been measured based on Fig. 5 (A) and the results has been manipulated.

Figure 8. Velocity graph at the smooth surface topography

Fig. 8 shows that there was no velocity as the bottom, but there was little velocity at the mid and top. There is a dramatic increase in the end of the topography. The top line shows the highest velocity near to 0002 m/s.
Next is the velocity at Fig. 9 which shows the circular surface topography.

![Velocity graph at the circular surface topography](image)

**Figure 9.** Velocity graph at the circular surface topography

Fig. 9 shows that the bottom line is 0 m/s and there was an up and down hill, that is because the circular topography has a spacing between each other but the maximum velocity resulting in top line is around 0.0051 m/s.

By comparing the maximum velocity in Fig. 8 and Fig. 9, the chances of biofouling will attach on the surface is Fig. 8 (smooth surface). Once the velocity has been manipulated, wall shear will then be investigated, and wall shear is very important for knowing the performance of antifouling.

### 3.2 Wall Shear

The wall shear is another concern for antifouling. As the higher the wall shear, the more effective the wall shear will be for antifouling. Fig. 10 shows the wall shear in smooth topography.
The wall shear in smooth surface topography was constant throughout the whole topography but at the start and end of the smooth topography, there are some red and yellow colour. But the bottom wall below the topography is in blue which is 0 Pa. Fig. 11 is the graphical with the top, mid and bottom line of the topography.

In Fig. 11 clearly shows that the bottom line of the smooth topography was near to 0 Pa. Besides that, there were wall shear on the beginning of top and mid line and higher wall shear at the end of the topography, which the highest wall shear can be around 0.45 Pa. In Fig. 12 shows the wall shear on the circular surface topography.
In Fig. 12, the wall shear on the top line is not constant like smooth topography. There are colours from green to red at the top line of this circular topography, especially the topography near the outlet there are majority red colour on it. However, the bottom line of the topography is in blue which has the lowest wall shear. According to the side view of the scope image on Fig. 12, the top is red which has the higher wall shear and decreases on wall shear until the bottom of the circular surface. In Fig. 13 is the graphical of the wall shear.

This Fig. 13 has shown in scatter plot because it has a more detailed look for it in a scatter plot form. There is spacing in between the circular topography which makes the value in mid line and top
line to be up and down. But by getting the highest wall shear will be on the top line which is around 0.6 Pa. By comparing the maximum wall shear in Fig. 11 and Fig. 12, Fig. 13 (circular topography) has higher wall shear.

3.3 Further Discussion

Tab. 5 shows the maximum velocity and maximum wall shear for smooth and circular topography.

Table 5. The velocity and wall shear maximum value

| Topography | Max. Velocity (m/s) | Max. Wall Shear (Pa) |
|------------|---------------------|----------------------|
| Smooth     | 0.0019              | 0.43                 |
| Circular   | 0.0053              | 1.23                 |

In Tab. 5 clearly shows the maximum velocity in smooth and circular topography that circular has higher velocity and based on the maximum wall shear, the circular also has the higher wall shear.

Based on the results and summarise, the antifouling with the circular topography is higher compared to the smooth topography. The project research is about the increasing gradient complexity of the topology and manipulating the efficacy. As smooth topography has less complexity gradient compared to circular topography which has more complexity gradient, therefore, after this research and numerical results, this study can show that the higher the complexity in gradient will have higher efficacy on antifouling.

4. Conclusion

As circular topography has higher gradient complexity and smooth surface topography has the least gradient complexity, there was increasing gradient complexity from smooth to circular topographies. As the results are manipulated, circular topography has higher velocity and wall shear compared to the smooth topography. This can be concluded by stating that with increasing gradient complexity, the velocity and wall shear will increase. Therefore, the efficacy of antifouling performance also increases. This study is mainly for filtration membrane surfaces in water treatment systems, where surface modification has high potential to use in filtration membranes in water treatment systems. Surface modification can also be used in all kinds of industrial because this method was not toxic and contain high potential of antifouling performance when the gradient complexity is very high. Selection of topography will be based on choosing the high gradient complexity to perform efficacy antifouling performance.

5. References

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