CFD-DEM modelling of biofilm streamers oscillations and their interactions in the flow

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Abstract

Biofilm streamer motion under different flow conditions is important for a wide range of industries. The existing work has largely focused on experimental characterisations of these streamers, which is often time-consuming and expensive. To better understand the physics of biofilm streamer oscillation and their interactions in fluid flow, a CFD-DEM (Computational Fluid Dynamics – Discrete Element Method) model has been developed. The model was used to study the flow-induced oscillations of single and multiple biofilm streamers. We have studied the effect of streamer length on the oscillation at varied flow rates. The predicted single biofilm streamer oscillations in various flow rates agreed well with experimental measurements. Furthermore, we have investigated the effect of the spatial arrangement of streamers on interactions between two oscillating streamers, which have not been achieved previously.

Keywords: biofilm streamers, biomechanics, discrete element modelling, computational fluid mechanics

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1. Introduction

Biofilms are microorganisms attaching and growing on surfaces, embedded in an extracellular polymeric substances (EPS) (Garrett, Bhakoo, & Zhang, 2008; Walter, Safari, Ivankovic, & Casey, 2013). Flow-induced biofilms deformation can lead to erosion and detachment, which are important for biofilm control and management (Rusconi, Lecuyer, Guglielmini, & Stone, 2010; Stoodley, Sauer, Davies, & Costerton, 2002). Klapper *et al.* found that extracellular matrix can hold the cells together to develop filament-like biofilm structures and suspended freely with fluid flow (Klapper, Rupp, Cargo, Purvedorj, & Stoodley, 2002). Besides, such a filament structure can also form in porous media or patterned surfaces even in laminar flow condition (Drescher, Shen, Bassler, & Stone, 2013; Hassanpourfard et al., 2015). Such filamentous structures of biofilms are referred to biofilm streamers and can accelerate the biofilm induced clogging of medical stents and water purification filters (Drescher et al., 2013). The characteristics and formation of biofilm streamers have been initially investigated under turbulent flow by Stoodley *et al.* (Stoodley, Lewandowski, Boyle, & Lappin-Scott, 1998). Later, biofilm streamers have also been observed in laminar flow with low Reynolds numbers at 0.01 and 120 (Rusconi et al., 2010; Stoodley, Cargo, Rupp, Wilson, & Klapper, 2002). It was found that the oscillation frequency of the biofilm streamer increased with the average flow velocity. In addition to studying single biofilm streamer deformation in the flows, it is also important to explore flow-induced interactions between biofilm streamers which is difficult to be investigated in laboratory experiments. Therefore, computational modelling of biofilm streamers would be important to get a physical insight about streamer dynamics and could be used to assist experimental design. On the other hand, only continuum models have been so far adapted to study the oscillatory motion of a single biofilm streamer under different flow conditions (Taherzadeh et al., 2010). However, the predicted amplitude of biofilm streamer oscillation did not agree with the experimental measurements at lower flow velocities. This

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may be attributed to the 2D nature of the biofilm streamer structure. The main disadvantage of a continuum model of biofilm is that it is rather difficult to include biofilm heterogeneity in the model compared to discrete models. Therefore, a novel discrete model of biofilm streamers was proposed to simulate biofilm streamer oscillations in fluid flows. The streamers are modelled using the discrete element method (DEM) and the flow field is computed using Computational Fluid Dynamics (CFD). The DEM was initially developed to study mechanics of granular like materials (Gu, Ozel, & Sundaresan, 2016; Schrader et al., 2019; Sun, Xiao, & Sun, 2017) and has been recently extended to investigate mechanics of living materials such as biofilms (Jayathilake, Li, Zuliani, Curtis, & Chen, 2019; Li et al., 2019), cells and tissues (Elvitigala et al., 2018; Kleinstreuer & Xu, 2018). The CFD-DEM model was implemented on SediFoam (https://github.com/xiaoh/sediFoam) which is an open source C++ tool kit based on LAMMPS (Plimpton, 1993) (Large-scale Atomic/Molecular Massively Parallel Simulator) and OpenFOAM (Greenshields, 2017) (Open-source Field Operation and Manipulation). The objectives of the present study are to (1) demonstrate the capability of CFD-DEM of predicting biofilm streamer deformation in flows, (2) investigate how the spatial arrangement between biofilm streamers effects on the deformation of streamers.

2. Methodology

2.1 Discrete element method for particle motion

In our model, each DEM particle represents a cluster of biofilms. In the CFD-DEM approach, the calculation of DEM particle motion is based on Newton's second law as the following equations:

$$m\frac{d\vec{v}}{dt} = \vec{F} = \vec{F}_c + \vec{F}_{coh} + \vec{F}_{fp} \quad (1)$$

where $\vec{v}$ is the velocity of the particle; m is particle mass; $\vec{F}_c$ is the contact force among collided particles, $\vec{F}_{coh}$ is inter-particle cohesive force, $\vec{F}_{fp}$ is fluid-particles interaction force. The

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contact forces between two nearby DEM particles are calculated using the Kelvin-Voigt model as (LAMMPS Manual):

$$F_c = \sqrt{\delta}\sqrt{\frac{r_i+r_j}{r_i r_j}}\left[\left(k_n\delta\vec{n}_{ij} - m_{eff}\gamma_n\vec{v}_n\right) - \left(k_t\Delta\overrightarrow{S_t} + m_{eff}\gamma_t\vec{v}_t\right)\right] \quad (2)$$

where δ is the overlap between the two particles, r_i and r_j are the diameter of two particles in the vicinity, k_n and k_t are the elastic constants for normal contact and tangential contact, γ_n and γ_t are respectively the normal damping coefficient and tangential damping coefficient, $m_{eff} = m_i m_j/(m_i + m_j)$ is the effective mass among the two particles, $\overrightarrow{S_t}$ is the vector of tangential displacement between the two agents, n_{ij} is the normal vector between the two particles, $\vec{v}_n$ and $\vec{v}_t$ are the normal component and tangential component of the relative velocity vector between the two particles.

2.2 Cohesive model

Apart from the contact forces between bacteria, there should be other forces like van der Waals attraction (Rajagopalan & Hiemenz, 1997), pili mediates intercellular adhesion (Xu et al., 2013) and EPS adhesion between bacteria, these forces will contribute to the mechanical stability of the biofilm. All these cohesive forces will be combined and represented by a formula which is similar to van der Waals (Israelachvili, 2011; Sun, Xiao, & Sun, 2018) as:

$$F_{coh} = -\frac{A}{6}\frac{64r_i^3 r_j^3(s+r_i+r_j)}{(s^2+2r_i s+2r_j s)^2(s^2+2r_i s+2r_j s+4r_i r_j)^2}\overrightarrow{n}_{ij} \quad (3)$$

where A is the combined cohesive strength, s is the separation distance between the particle surface. A minimum separation distance s_{min} is implemented when the distance between the two particles equals to zero.

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2.3 Locally-Averaged Navier-Stokes equation for fluids

The fluid flow is described by locally-averaged incompressible Navier-Stokes equation. Assuming constant fluid density ρ_f, the governing equations for the fluid are(Sun & Xiao, 2016):

$$\nabla \cdot \left(\epsilon_s \vec{U}_s + \epsilon_f \vec{U}_f\right) = 0, \tag{4}$$

$$\frac{\partial(\epsilon_f \vec{U}_f)}{\partial t} + \nabla \cdot \left(\epsilon_f \vec{U}_f \vec{U}_f\right) = \frac{1}{\rho_f}(-\nabla p + \epsilon_f \nabla \cdot \vec{R} + \epsilon_f \rho_f \vec{g} + \vec{F}_{fp}) \tag{5}$$

ϵ_s is solid volume fraction while ϵ_f is fluid volume fraction which equals to (1-ϵ_s). $\vec{U}_s$ and $\vec{U}_f$ are particle velocity and fluid velocity, respectively, $\vec{F}_{fp}$ is the fluid-particle interaction force. ∇p is the pressure gradient, g is gravity and $\vec{R}$ is the stress tensor consisting of viscous stress and Reynolds stress. In this study, to simplify the simulations, Reynolds stress has not been considered as the Reynolds number is very small.

2.4 Fluid-particle interaction

The drag force model is adopted to calculate the fluid -particle interaction force(Sun et al., 2018) as:

$$\vec{F}_{fp} = \frac{V_{p,i}}{\epsilon_{f,i}\epsilon_{s,i}} \beta_i \left(\vec{U}_{f,i} - \vec{u}_{p,i}\right) \tag{6}$$

Where $V_{p,i}$ is the volume of the particle, $\vec{U}_{f,i}$ and $\vec{u}_{p,i}$ are the fluid velocity and particle velocity, respectively. $\epsilon_{f,i}$ is fluid volume fraction while $\epsilon_{s,i}$ is solid volume fraction, β_i is the drag correlation coefficient which is used to convert terminal velocity correlation to drag correlation (Sun et al., 2018; Syamlal, Rogers, O'Brien, & Documentation, 1993).

3. Model Domain

Three different case studies were considered: (1) single biofilm streamer (Fig. 1A); (2) two biofilm streamers in parallel (Fig.1B); (3) two biofilm streamers in tandem (Fig.1C).

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The streamer dimensions were taken from experimental measurements reported in (Stoodley et al., 1998). The streamer tail was created by 14 particles (light blue particles in Fig.1A), which was flexibly attached to a stationary biofilm cluster (red particle in Fig.1A). The biofilm cluster with diameter (D_c) of 0.34mm was fixed in all directions. The length (L) of streamer is 1.492mm. To enable direct comparisons, the simulation box was chosen to be a rectangular channel with the same dimensions (length : 12mm, height: 3.2mm) to another modelling work by Taherzadeh, D., et al. (Taherzadeh et al., 2010). In addition, a small value of width (L_z = 0.5mm) was chosen in z direction since empty boundary condition is applied to the front and back wall to simplify the simulation.

A uniform velocity profile was implemented at inlet flow boundary (x = 0). The velocity was fixed at the inlet of the channel and had a zero gradient boundary condition at outlet. The deformation of the streamer was only monitored after it reached constant maximum amplitude. The pressure here was enforced as zero gradient at the inlet patch and zero value at the outlet patch. Slip boundary condition was used at the top and bottom walls, which assumed the viscous effects at the wall are negligible. Therefore, the simulation domain could be reduced since there is no thin boundary layer on the channel walls (Song & Perot, 2015; Taherzadeh et al., 2010).

Table 1 shows the simulation parameters. Depending on biofilm types, growth conditions and test approaches, the Young's modulus of biofilms could vary several orders of magnitude (Guhados, Wan, & Hutter, 2005; Hsieh, Yano, Nogi, & Eichhorn, 2008; Konhauser & Gingras, 2007; Stoodley, Cargo, et al., 2002). In this work, the equivalent Young's modulus of biofilm was 10Pa which is similar to the biofilm streamer of mixed *P. aeruginosa* strains as reported in (Stoodley, Cargo, et al., 2002). A large combined cohesive energy was chosen to represent cohesive properties of the biofilm streamer (Ahimou, Semmens, Novak, & Haugstad, 2007; Malarkey et al., 2015) since EPS is the major component in biofilm streamer (Das & Kumar,

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2014). The bacteria density was often very similar to water with 1% difference (Storck, Picioreanu, Virdis, & Batstone, 2014), we have demonstrated that such mirror difference has negligible effect. In this case, it was assumed to be the same to water.

3.1 Single streamer

The biofilm streamer length (L) was normalized regarding the maximum width (D_c) in this section. We initially investigated the deformation of a single streamer (L/D=4.4) subjected to flow velocity from 0.1m/s to 0.4m/s. However, the length of streamer varied in experiments because of different biofilm types and flow conditions (Milferstedt, Pons, & Morgenroth, 2009; Raunkjær, Nielsen, & Hvitved-Jacobsen, 1997). As reported in (Stoodley et al., 1998), the maximum length of mixed population biofilm streamer is up to 3mm. Therefore, it was useful to study the effect of the length of biofilm streamer on its oscillation. Similar to the setup of continuous biofilm streamer model, lower values of L/D (i.e. 1 and 2.5) were also investigated (Taherzadeh et al., 2010).

3.2 Two streamers in parallel

Two parallel biofilm streamers were considered to study the interaction between them. As shown in figure 1B, the spacing distance *l* (i.e. the centreline distance of the two streamer tails) varied from 0.4–1.113L while the velocity was fixed at 0.4m/s. The effect of flow velocity on biofilm streamer interaction was also be studied by keeping spacing distance as constants.

3.3 Two streamers in tandem

In this case, we varied the spacing distance *h* (i.e. distance between the tip of the leading streamer and the biofilm cluster of the trailing streamer) between 0 and 2L. This configuration is well known for the hydrodynamic drafting of the fixed shape, which refers to the fact that the downstream objects are generally subjected to a reduced drag force (Ristroph & Zhang, 2008). However, for deformable materials, such as biofilm streamer, the fluid structure

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interaction is poorly understood. In addition, their oscillation under different flow conditions have been investigated by keeping spacing distance *h* as constants.

4. Results and discussion

4.1 Oscillation of one single biofilm streamer in an incoming fluid flow

The oscillation amplitude and frequency were investigated for the flow velocity between 0.025 and 0.4 m/s. Figure 2A shows the streamer configuration and corresponding velocity field at 0.05s at flow velocity of 0.4 m/s. The corresponding Reynolds number was equal to 136 by using the biofilm cluster diameter D_c as the characteristic length. It could be seen that the vortexes generated when flow passes the biofilm cluster and continuously shed from each side of this cluster, resulted in streamer beating. Figure 2B displays the maximum displacement and oscillation frequency of the biofilm streamer. The predicted maximum displacement and oscillation frequency of the streamer tip were 191.2μm and 220Hz, respectively, which quantitatively agreed with experimental observations of (Stoodley et al., 1998).

Figure 2C presents the biofilm streamer oscillation amplitudes determined by experimental measurements (Stoodley et al., 1998), a continuum model (Taherzadeh et al., 2010) and the present study. At the considered flow velocities, it seemed that there were three stages of streamer oscillation characteristics predicted by CFD-DEM simulations : (1) Stage 1: biofilm streamer slightly vibrated at very low fluid flow velocity; (2) Stage 2: vibration amplitudes increased sharply when the velocity exceeds 0.1m/s (comparable to the 0.075*m/s* as found in experimental measurements); (3) Stage 3: The increase of maximum amplitude of streamer tip slowed down when velocity exceeds 0.15 *m/s* which was very close to the transition point (0.2m/s) found in experimental measurements (Stoodley et al., 1998).

When flow velocity rose to 0.25 m/s, the amplitude in the present simulations almost reached plateau, about 200.1μm and remained well with further increased velocity. Meanwhile, biofilm

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oscillation amplitude in the experiment was around 209.3μm at similar velocity (0.253m/s) and sustainably grew with velocity.

Figure 3A displays the oscillation amplitudes of biofilm streamer with different L/D_c subjected to varied flow velocities. The streamer oscillation amplitude was proportional to their tail length under the same flow condition. In addition, the peak displacement of each biofilm streamer occurred when the flow velocity is around 0.25m/s and slightly decreased with further increase in velocity. Besides, it was noted that for streamers of various lengths, the oscillation amplitudes were all very small when the velocity is under 0.1m/s (Reynolds number =34). It could be because the viscous force is dominant at low flow velocity and drains eddy energy to against vortex shedding. Similar results were found by Sumer *et al* that when Reynolds number is under 40, there is only a fixed pair of symmetric vortices and has no vortex shedding (Sumer, 2006). In our simulations, the oscillation was observed when Reynolds number is far greater than 34 which suggested that the streamer oscillation was directly caused by vortex.

As seen in figure 3B, the frequency of streamer oscillation increased with flow velocity which was in agreement with the experimental observations (Stoodley et al., 1998). However, the oscillation frequency appeared independent from the streamer length. Since the oscillation of streamer was caused by the vortex shedding from upstream biofilm cluster, the dimensionless parameter Strouhal number (S_t) is commonly adopted to describe the oscillation (Asyikin, 2012; Stoodley et al., 1998; Taherzadeh et al., 2010) as:

$$S_t = \frac{f D_C}{u} \tag{7}$$

The diameter of upstream biofilm cluster D_c is use as the characteristic length here, f is the flow oscillation frequency and u is the velocity of the fluid flow. Figure 3C displays the Strouhal number dependency on Reynolds number. S_t increased with Reynolds number and was close to 0.2 when the Reynolds number exceed 104, which was consistent with the results from other simulations (Oliveira, 2001; SARIOĞLU & Yavuz, 2000).

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4.2 Two streamers in side-by-side arrangement

Vortex shedding may occur when flow passes two big biofilm clusters, which may also lead to streamer oscillation. Different regimes of biofilm streamers interaction depending on the spacing between them have been observed and presented in the following as a function of the ratio of spacing distance to biofilm length *l*/L.

An image of biofilm streamer experiment (Stoodley et al., 1998) has shown two parallel streamers which are head-aligned and similar-sized, they remained well and flapped in the flow. Likewise, the spacing distance (l/L = 0.4) between two side-by-side biofilm streamers was initially adopted in the model. As displayed in figure 4A, the two biofilm streamers behaved as twin streamers due to in-phase flapping. The maximum oscillation amplitudes of the two streamers were about the same, 126.2μm and 126.4μm, respectively (see Figure S1A). In addition, the oscillation frequency of both two streamers was about 250Hz (see Figure S1A). The maximum amplitude here was smaller than the amplitude of single flapping streamer due to the strong mutual interaction between them which caused by coupled near-wakes.

When *l/L* exceeded 0.56 (see Figure 4B), the two steamers oscillated on an out-of-phase mode. In this case, the maximum amplitude and frequency of these two streamers were the same, 154.3μm and 250Hz (see Figure S1B). As presented in figure 4C, when further increasing the gap equal to streamer length (*l/L* =1), the interaction between the two biofilm streamers weaken due to the reduction of mutual interference among them. The maximum amplitude of oscillation slightly raised to 175.15μm while frequency kept at 250Hz (see Figure S1C). These results suggested that as the spacing distance increased, oscillation amplitude of two parallel streamer rose, however, frequency remained same. As displayed in figure 5, a positive correlation was found between oscillation amplitude and spacing distance. The graph shows a sharp rise in oscillation amplitude during the in-phase flapping regime ($0.4 < l/L < 0.51$). On the out-of-phase oscillation mode ($l/L > 0.56$), the maximum amplitude of oscillation slightly

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grew with the spacing distance and finally remained around 175.21μm. One reason for this phenomenon may be the vortex shed from two biofilm clusters and strongly affect each other on the out-of-phase mode. It is important to note that the oscillation frequency did not change in all cases because of consistent flow velocity. This indicated that the frequency only related to the fluid velocity which agrees with previous results of single streamer oscillation. To further verify this hypothesis, fluid velocity has been decreased for side-by-side streamers at spacing distance l/L = 1. As a result, oscillation frequency of these two streamers decreased to 180Hz when the fluid velocity is 0.3m/s (see Figure S2A), further declined to 120Hz at fluid velocity of 0.2m/s (see Figure S2B), which are comparable to what was shown in figure 3B. Besides, there was no significant change in oscillation amplitude.

4.3 Two biofilm streamers in tandem arrangement

For two biofilm streamers in tandem arrangement, when the spacing distance was zero, the tail of upstream streamer initially adhered to the biofilm cluster of the downstream streamer because of the cohesive force (see Figure 6). After around 0.035s, the oscillation started from the downstream streamer because the fluid behind it could move freely. Meanwhile, the leading streamer tended to oscillate which finally caused the last particle detached from the upstream streamer and reattached to the downstream biofilm cluster. Afterwards, the remaining upstream biofilm streamer flapped in the flow due to the vortex shedding.

A different behaviour was captured when the spacing distance is increased to h/L = 0.25. As seen in figure 7A, it was apparent that the upstream streamer particles are staggered and moved along the opposite direction of the x-axis. This phenomenon suggested that the upstream biofilm streamer was affected by a recirculating flow. The velocity vectors are displayed in figure 7B, the flow separated at the upstream biofilm cluster and then reattached at the downstream biofilm cluster, thus a recirculating zone generated between them which caused

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upstream biofilm streamer moving against flow. This recirculating zone disappeared over time as shown in figure S3. However, the upstream biofilm streamer was still stationary since the shear layer enclosed the gap between two biofilm clusters. It started beating the flow at time of 0.04s when the shear layer was about to break which resulted in vortex formation. Subsequently, the already flapping downstream biofilm streamer also experienced the impingement of the vortex which is shed from the upstream biofilm cluster. Thereby, the downstream streamer had a large deformation during this period (see figure S4). Then the vortex shed from the upstream biofilm cluster gradually merged with those forming from the downstream biofilm cluster and totally coupled at around 0.09s caused an out-of-phase flapping of two streamers. The deformation of downstream streamer weakened after the co-shedding process since the combined vortices became weaker. In the same vein, the results in figure S4 shows that the maximum displacement of the tip of downstream streamer sharply increased during impingement period, then slowly decreased during the co-shedding period and finally reached a minimum value equal to 187.75μm. The oscillation amplitude of upstream streamer kept around 195.6μm. In addition, oscillation frequency of these two streamers were the same here about 220Hz.

The initial reattachment region disappeared when the gap *h/L* reached 0.75. As displayed in figure 8A, the leading biofilm streamer beat the flow firstly because of the vortices shedding when the flow passes the leading biofilm cluster, then the trailing streamer beat the flow immediately. The results, as shown in figure 8B, indicated that the two streamers beat the flow simultaneously. In this case, the oscillation amplitude of upstream biofilm streamer remains around 188.9μm. Similarly, the downstream streamer also had large deformation during impingement period and flapped gently after co-shedding period with oscillation amplitude of 114.45μm. Frequency of oscillation kept at 220Hz because of the unchanged flow velocity.

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Figure 9 shows the oscillation amplitude of downstream streamer was always smaller than that of the upstream streamer at fluid flow velocity of 0.4 m/s. This agrees with the drafting effect that the downstream object experienced a lower flow stress. In addition, the oscillation amplitude of the downstream streamer decreased with increasing gap *h/*L, which illustrated that the downstream streamer would subject to a smaller drag force with increasing spacing distance.

Biofilm streamer oscillation at different velocity has been investigated by keeping the spacing distance *h/L* as 1. Flow velocity here was varied from 0.2m/s to 0.4m/s since biofilm streamer has significant oscillation when flow velocity was greater than 0.1m/s. Consistent with previous results, the frequency of inline flapping streamers increased with flow velocity (see figure S5 and S6). However, it was found that the oscillation amplitude of upstream streamer was smaller than it of downstream streamer at flow velocity of 0.2m/s, which indicated that the drafting effect was not straightforwardly inherited by the flapping streamer at smaller flow velocity. This invert drafting effect has also been found in other deformable bodies, such as the experimental and numerical researches of flapping soap films (Favier, Revell, & Pinelli, 2015; Ristroph & Zhang, 2008).

5. Conclusions

In this work, CFD-DEM models have been developed to predict oscillation of biofilm streamers with different configurations in uniform fluid flow. For the single biofilm streamer, the biofilm streamer vibration predicted by our computational modelling agreed well with the experimental measurements (Stoodley et al., 1998), which has not been achieved by previous models such as the continuum modelling (Taherzadeh et al., 2010). The simulations have demonstrated that the oscillation frequency of biofilm streamer is affected by the fluid velocity but independent from the length of streamer. The oscillation amplitude of biofilm streamer is influenced by their length and flow velocity.

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For side-by-side biofilm streamers, in-phase oscillation took place at small gaps ($0.4 < l/L < 0.51$). At intermediate and large spacing distances, streamers flapped on an out-of-phase mode. The oscillation amplitude increased with spacing distance and reached a peak value due to decoupled flapping. However, the maximum amplitude was still smaller compared to single streamer because of strong wake interaction.

For biofilm streamers in tandem, the detachment of streamer tip and recirculating zone occurred at small gaps ($h/L<0.75$). When the fluid velocity was greater than 0.3m/s, the oscillation amplitudes of the downstream streamer were smaller than it of upstream streamer. However, an invert drafting effect has been found at lower fluid velocity, in which case the upstream streamer experiences a drag reduction.

Future work would consider multiple biofilm streamers in 3D fluid flow since biofilm streamers are ubiquitous and may cause channel clogging.

Conflict of Interest:

There are no conflicts to declare.

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Table

Table 1. Simulation parameters

Numerical simulation parameters	
Density of particles	1000kg/m^3
The equivalent Young's modulus of biofilm streamer	10Pa
Cohesive strength	1×10^{-15}J
Fluid dynamic viscosity	1×10^{-3}kg/ (m s)
Fluid density	1000kg/m^3

Figure Legends:

Figure 1: Summary of the model for (**A**) single biofilm streamer, (**B**) side-by-side biofilm streamers and (**C**) in-line biofilm streamers.

Figure 2: (A) Streamer oscillation and velocity field. **(B)** The temporal vibration amplitudes of inline biofilm steamers tip at flow velocity of 0.4m/s. (**C**) Maximum amplitudes of biofilm steamer tip

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determined by the present study and experiments results [8] as well as numerical simulations reproduced in (Stoodley et al., 1998; Taherzadeh et al., 2010).

Figure 3: The (A) oscillation amplitudes, (B) frequency of streamer of different length and (**C**) Strouhal number vs Reynolds number for fluid velocity ranging from 0.1 to 0.4m/s.

Figure 4: The oscillation and flow field of two side-by-side biofilm streamers with (A) *l*/L =0.4, (B) 0.56 and (C) 1 at v=0.4m/s and t=0.1s.

Figure 5. Maximum oscillation amplitude of side-by-side biofilm streamers varying spacing distance *l/L* from 0.4 to 1.13, v=0.4m/s.

Figure 6: Temporal vibration for in-line streamers with h/L =0, at flow velocity of 0.4m/s.

Figure 7. The behaviours of inline biofilm streamers (h/L = 0.25) at v=0.4m/s and t=0.08s.

Figure 8. (**A**) The flow pattern and oscillation of inline biofilm streamers (h/L = 0.75) at flow velocity of 0.4m/s at 0.015s and 0.02s. (**B**) The temporal vibration amplitudes of inline biofilm steamers tip at flow velocity of 0.4m/s.

Figure 9. Maximum oscillation amplitude of inline biofilm streamers with different spacing distance (h/L) at flow velocity of 0.4m/s.

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