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ARTICLE

CFD–DEM modelling of biofilm streamer oscillations and their cohesive failure in fluid 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 computational fluid dynamics–discrete element method model has been developed. The model was used to study the flow-induced oscillations and cohesive failure 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. We have also investigated the effect of the spatial arrangement of streamers on interactions between two oscillating streamers in parallel and tandem arrangements. Furthermore, cohesive failure of streamers was studied in an accelerating fluid flow, which is important for slowing down biofilm-induced clogging.

KEYWORDS

biofilm streamers, biomechanics, computational fluid dynamics, discrete element model

1 | INTRODUCTION

Biofilms are microorganisms attaching and growing on surfaces, embedded in their extracellular polymeric substances (EPS; Garrett et al., 2008; Walter et al., 2013). It is well known that biofilms have a significant impact on environment, human health, and a wide range of industries. For example, they play an important role in biological waste-water treatment (Zhao et al., 2019). The presence of biofilms is the major cause for infections of medical devices (Cao et al., 2018; Hall-Stoodley & Stoodley, 2009) and the clogging of industrial flow system, such as biofouling in membrane system (Vrouwenvelder et al., 2010). They also lead to increased drag on marine vessels (Fabbri et al., 2018). Biofilms can adapt to different environments by forming diverse morphologies (Wang et al., 2016). For example, the extracellular matrix can hold the cells together to develop filament-like biofilm structures to resist the fluid shear force and suspended freely with fluid flow (Klapper et al., 2002). Such filamentous structures of biofilms are

referred to biofilm streamers which are ubiquitous in porous media and can accelerate the biofilm-induced clogging of medical stents and water purification filters (Drescher et al., 2013; Hassanpourfard et al., 2015; Marty et al., 2012). Valiei et al. (2012) fabricated a microfluidic device with an array of micro-pillars to mimic a porous media and they found that biofilm streamers began to emerge between different pillars. It is also found that streamers can form in curved sections of microchannel (Rusconi et al., 2010). A lot of work has demonstrated that biofilm streamers act as precursors to the formation of mature and denser biofilms in porous media, causing rapid and catastrophic clogging in biomedical systems (Drescher et al., 2013; Marty et al., 2012; Taherzadeh et al., 2010; Valiei et al., 2012). In which case, the interactions between biofilm streamers and fluid flow are important but remain elusive.

Stoodley et al. (1998) have performed experiments to study the flow induced biofilm streamer oscillations, and found that the streamer displacement increased with flow velocity and oscillate in a

sinusoidal curve. However, the interaction of local flow with biofilm streamer is difficult to be examined experimentally. Therefore, a continuum model has been developed to study the oscillatory motion of a single biofilm streamer under different flow conditions (Taherzadeh et al., 2010). Such a continuum model gave reasonable predictions about the overall streamer oscillation characteristics, however, it significantly underestimated the oscillation amplitude of a streamer at low flow velocities. Furthermore, such a model could not predict the breakup of the streamers which has been observed in the experimentation in Stoodley et al. (1998). In either natural or artificial scenarios, multiple streamers can form at the same time. These streamers can spatially organise in different patterns. However, there is a lack of computational studies about fluid–structure interactions of multiple biofilm streamers arranged in different spatial configurations. Therefore, this study presents a new computational model to study single and multiple biofilm streamer oscillation and their cohesive failure under different fluid flow. 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 et al., 2016; Schrader et al., 2019; Sun et al., 2017) and has been recently extended to investigate mechanics of living materials such as biofilms (Jayathilake et al.,

2017, 2019; Li et al., 2019), cells and tissues (Elvitigala et al., 2018; Kleinstreuer & Xu, 2018). The present model was implemented on SediFoam (<https://github.com/xiaoh/sediFoam>) which is an open source CFD-DEM tool kit based on large-scale atomic/molecular massively parallel simulator (LAMMPS; Plimpton, 1993) and Open-source Field Operation and Manipulation (OpenFOAM; Green-shields, 2017). The objectives of the present study are to (1) demonstrate the capability of CFD-DEM of predicting biofilm streamer oscillation in flows, (2) investigate how the spatial arrangement between biofilm streamers effects on the oscillation of streamers, (3) how the flow conditions and spatial arrangement effect on cohesive failure of biofilm streamers.

2 | METHODOLOGY

2.1 | Discrete element method for particle motion

The conceptual biofilm streamer was constructed by 15 particles with decreasing radii as shown in Figure 1a. Each particle has representative properties of biofilms. In the CFD-DEM approach, the particle motion is calculated based on Newton's second law as the following equations:

FIGURE 1 Summary of the model for (a) single biofilm streamer, (b) side-by-side biofilm streamers and (c) in-line biofilm streamers [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

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

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 interparticle cohesive force, $\vec{F}_{fp}$ is fluid-particles interaction force. The contact forces between two collided DEM particles i, j are calculated using the Kelvin-Voigt model as (LAMMPS manual):

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

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, $\vec{S}_t$ is the vector of tangential displacement between the two agents, $\vec{n}_{ij}$ 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 (Figure S1).

2.2 | Cohesive model

The cohesive force among the biofilm particles is represented by the following formula (Israelachvili, 2011; Sun et al., 2018):

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

where A is the 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.

2.3 | Locally-averaged Navier–Stokes equations for fluids

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

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

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

where ϵ_s is solid volume fraction while ϵ_f is fluid volume fraction which equals to $(1 - \epsilon_s)$. $\vec{U}_s$ 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, $\vec{g}$ is gravity and $\vec{R}$ is the stress tensor consisting of

viscous stress and Reynolds stress. In this study, to simplify the simulations, the Reynolds stress has not been considered as the Reynolds number is very small (34–136).

2.4 | Fluid–particle interaction

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

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

where $V_{p,i}$ is the volume of the particle i , $\vec{U}_{f,i}$ 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 et al., 1993).

3 | MODEL DOMAIN

Three different case studies were considered: (1) single biofilm streamer (Figure 1a); (2) two biofilm streamers in parallel (Figure 1b); (3) two biofilm streamers in tandem (Figure 1c). The streamer dimensions were taken from experimental measurements reported in (Stoodley et al., 1998). The streamer tail (light blue particles in Figure 1a) adhered to its stationary spherical base which was represented as a biofilm cluster (red particle in Figure 1a). The biofilm cluster with diameter (D_c) of 0.34 mm was fixed in all directions. The length (L) of the streamer is 1.492 mm. The simulation box was chosen to be a rectangular channel with the same dimensions (length: 12 mm, height: 3.2 mm) to another modelling work in Taherzadeh et al. (2010). In addition, a small value of width ($L_z = 0.5$ mm) was chosen in the z -direction since an 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. To avoid boundary effects on the streamers, slip boundary condition was used at the top and bottom walls such that there is no boundary layer development on the channel walls (Song & Perot, 2015; Taherzadeh et al., 2010).

Table 1 shows the key input parameters for the simulations. Depending on biofilm types, growth conditions and test approaches, the Young's modulus of biofilms could vary over several orders of magnitude (Guhados et al., 2005; Hsieh et al., 2008; Konhauser & Gingras, 2007; Stoodley et al., 2002). In this study, the equivalent Young's modulus of biofilm was 11 Pa which is similar to the biofilm streamer of mixed *P. aeruginosa* strains as reported in Stoodley

TABLE 1 Simulation parameters

Numerical simulation parameters	
Density of particles	1000 kg/m ³
The equivalent Young's modulus of biofilm streamer ($k_n = k_t$)	11 Pa
Cohesive strength	1×10^{-15} J
Fluid dynamic viscosity	1×10^{-3} kg/(m s)
Fluid density	1000 kg/m ³
Normal damping constants	10^{13} (m s) ⁻¹
Tangential damping constants	10 (m s) ⁻¹

et al. (2002). A large cohesive energy was chosen to represent cohesive properties of the biofilm streamer (Ahimou et al., 2007; Malarkey et al., 2015) since EPS is the major component in biofilm streamer (Das & Kumar, 2014). The bacteria density was often very similar to water with 1% difference (Storck et al., 2014), and we have demonstrated that such minor difference has negligible effect on the oscillation of single streamer. Therefore, the density of biofilm streamer was assumed to be the same to water in this study.

3.1 | Single streamer

The biofilm streamer length (L) was normalised by the maximum width (D_c) in this section. We initially investigated the deformation of a single streamer ($L/D_c = 4.4$) subjected to flow velocity from 0.1 to 0.4 m/s (corresponding Reynolds number 34–136, which was calculated by using D_c as the characteristic length). However, the streamer length varied in experiments because of different biofilm types and flow conditions (Milferstedt et al., 2009; Raunkjær et al., 1997). Therefore, it was useful to study the effect of the length of a biofilm streamer on its oscillation. In the present simulations, lower values of L/D_c (i.e., 1 and 2.5) were also investigated.

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 to 1.15 L while the inlet velocity was fixed at 0.4 m/s. The effect of flow velocity on the oscillation of parallel biofilm streamers was also investigated by keeping spacing distance as constant.

3.3 | Two streamers in tandem

In this case, we varied the spacing distance h (i.e., distance between the tail end of the upstream streamer and the head of the downstream streamer) between 0 and 2 L (Figure 1c) at inlet flow velocity

of 0.4 m/s. In addition, the streamers oscillation under different flow conditions have been investigated by keeping spacing distance h as constant.

4 | RESULTS AND DISCUSSION

4.1 | Oscillation of one single biofilm streamer in a fluid flow

The oscillation amplitude and frequency were investigated for the inlet flow velocity between 0.025 and 0.4 m/s. Figure 2a shows the streamer configuration and corresponding velocity field at 0.05 s at flow velocity of 0.4 m/s. It can be seen that the vortexes generated when flow passed the biofilm cluster and continuously shed from each side of this cluster, resulted in streamer oscillation. The predicted maximum displacement and oscillation frequency of the streamer tip were 198.5 μ m and 220 Hz (Figure 2b), respectively, which quantitatively agreed with experimental observations of Stoodley et al. (1998).

Figure 2c compares 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: oscillation amplitude increased sharply when the velocity exceeds 0.1 m/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 the velocity exceeds 0.15 m/s, which was very close to the transition point (0.2 m/s) found in experimental measurements (Stoodley et al., 1998).

When the flow velocity rose to 0.25 m/s, the amplitude in the present simulations almost reached plateau, about 200.1 μ m and remained steady with further increase in velocity. Meanwhile, the biofilm streamer oscillation amplitude in the experiment was around 209.3 μ m at similar velocity (0.253 m/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 0.25 m/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 (3.25–9.4 μ m) when the velocity is under 0.1 m/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 vortexes and no vortex shedding (Sumer, 2006). In our simulations, the oscillation was observed when Reynolds number is

FIGURE 2 (a) Flow patterns behind the streamer. (b) The temporal oscillation amplitudes of single biofilm streamer at flow velocity of 0.4 m/s. (c) Maximum amplitudes of biofilm streamer oscillation determined by the present study, experiments results as well as numerical simulations reproduced in (Stoodley et al., 1998; Taherzadeh et al., 2010) [Color figure can be viewed at wileyonlinelibrary.com]

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 the upstream biofilm cluster, the dimensionless parameter Strouhal number (S_t) could be adopted to describe the oscillation (Asyikin, 2012; Stoodley et al., 1998; Taherzadeh et al., 2010) as

$$S_t = \frac{fD_c}{u} \quad (7)$$

The diameter of the upstream biofilm cluster D_c is used as the characteristic length here, f is the frequency of vortex shedding and streamer oscillation, u is the inlet velocity of the fluid flow. The Strouhal number increased with Reynolds number initially and was close to 0.2 when the Reynolds number exceed 104 (Figure 3c), which was consistent with the results from other simulations of flow past cylinders (Oliveira, 2001; Sarioğlu & Yavuz, 2000).

4.2 | Two streamers in side-by-side arrangement

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 streamer 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 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. Vortex shedding formed when flow passed the side-by-side streamer clusters which led to streamers oscillation. 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, 126.2 and 126.4 μm , respectively (Figure S2A). In addition, the oscillation frequency of both streamers was about 250 Hz (Figure S2A). The maximum amplitude here was smaller than the amplitude of single flapping streamer due to the strong mutual interaction between them which could be caused by coupled near-wakes.

When l/L exceeded 0.56 (Figure 4b), the two streamers oscillated on an out-of-phase mode. In this case, the maximum amplitude

FIGURE 3 (a) Oscillation amplitudes, (b) frequency of streamer of different lengths and (c) Strouhal number versus Reynolds number for fluid velocity ranging from 0.1 to 0.4 m/s [Color figure can be viewed at wileyonlinelibrary.com]

and frequency of these two streamers were the same, 154.3 μm and 250 Hz (Figure S2B). As presented in Figure 4c, when further increasing the gap equal to streamer length ($l/L = 1$), the interaction between the two biofilm streamers weakened due to the reduction of mutual interference among them. The maximum amplitude of oscillation slightly grew to 175.15 μm while frequency kept at 250 Hz (Figure S2C). These results suggested that as the spacing distance increased, oscillation amplitude of two parallel streamers rose with the remained frequency. A positive correlation was found between oscillation amplitude and spacing distance (Figure 5). 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 grew with the spacing distance and finally remained around 175.21 μm . 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 behaviour, the fluid velocity has been decreased for side-by-side streamers at spacing distance $l/L = 1$. As a result, the oscillation

frequency of these two streamers decreased to 180 Hz when the fluid velocity is 0.3 m/s (Figure S3A), further declined to 120 Hz at fluid velocity of 0.2 m/s (Figure S3B), 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 the 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 their cohesive properties (Figure 6). After around 0.035 s, the oscillation started from the downstream streamer because the fluid behind it could move freely. Meanwhile, the upstream streamer tended to oscillate, which finally caused the cohesive failure at the streamer tip. Afterward, the remaining upstream biofilm streamer oscillated 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

FIGURE 4 Flow patterns behind two side-by-side biofilm streamers with (a) $I/L = 0.4$, (b) $I/L = 0.56$ and (c) $I/L = 1$ at the inlet velocity of 0.4 m/s and $t = 0.1 \text{ s}$ [Color figure can be viewed at wileyonlinelibrary.com]

opposite direction of the x -axis. This behaviour suggested that the upstream biofilm streamer was affected by a recirculating flow. Consequently, the recirculating zone was found between them which caused upstream biofilm streamer moving against flow (Figure 7b). This recirculating zone disappeared over time as shown in Figure S4. 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 0.04 s 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 shed from the upstream biofilm cluster. Thereby, the downstream streamer had a large deformation during this period (Figure S5). Then the vortex shed from the upstream biofilm cluster gradually merged with those forming from the downstream biofilm cluster and totally coupled at around 0.09 s causing an out-of-phase flapping of the two streamers. The

deformation of the downstream streamer weakened after the co-shedding process since the combined vortices became weaker. In the same vein, the results in figure S5 shows 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 $187.75 \mu\text{m}$. The oscillation amplitude of the upstream streamer kept around $195.6 \mu\text{m}$. In addition, oscillation frequency of these two streamers were the same here about 220 Hz .

The recirculating zone disappeared when h/L reached 0.75 . In this case, the two streamers could beat the flow simultaneously (Figure 8a). The oscillation amplitude of upstream biofilm streamer remains around $188.9 \mu\text{m}$. Similarly, the downstream streamer also had large deformation during the impingement period and flapped gently after the co-shedding period with an oscillation amplitude of $114.45 \mu\text{m}$. The frequency of oscillation kept at 220 Hz because of the unchanged flow

FIGURE 5 Maximum oscillation amplitude of side-by-side biofilm streamers changes with I/L (0.4 – 1.15) at the inlet flow velocity of 0.4 m/s [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Temporal oscillation of in-line streamers with $h/L = 0$, at flow velocity of 0.4 m/s [Color figure can be viewed at wileyonlinelibrary.com]

velocity (Figure 8b). The oscillation amplitude of downstream streamer decreased with the increase in spacing distance h/L , and the value was always smaller than that of the upstream streamer (Figure 9). This indicates the downstream streamer would undergo a smaller drag force when elevated the spacing distance. In contrast, the downstream streamer experienced a lower fluid stress which agreed with the draughting effect, which referred to the fact that the downstream object was generally subjected to a drag reduction compared to the upstream object (Ristroph & Zhang, 2008).

Biofilm streamer oscillation at different velocity has been investigated by keeping the spacing distance h/L as 1. Flow velocity here was varied from 0.2 to 0.4 m/s since the biofilm streamer has significant oscillation when the flow velocity was greater than 0.1 m/s. Consistent with previous results, the frequency of inline streamers oscillation increased with the flow velocity (Figures S6 and Figure S7). However, it was found that the oscillation amplitude of the upstream streamer was smaller than that of the downstream streamer at flow velocity of 0.2 m/s, which might suggest that the

FIGURE 7 The behaviours of inline biofilm streamers ($h/L = 0.25$) at $v = 0.4$ m/s and $t = 0.02$ s [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 (a) The flow pattern and oscillation of inline biofilm streamers ($h/L = 0.75$) at time of 0.015 and 0.02 s, flow velocity is 0.4 m/s. (b) The oscillation amplitudes of inline biofilm streamers at flow velocity of 0.4 m/s, $h/L = 0.75$ [Color figure can be viewed at wileyonlinelibrary.com]

draughting effect could not be straightforwardly inherited by the flapping streamer at smaller flow velocity. This invert draughting effect has also been found in other deformable bodies, such as experimental and numerical research of flapping soap films (Favier et al., 2015; Ristroph & Zhang, 2008).

4.4 | The cohesive failure of streamers

To study the cohesive failure of biofilm streamers, the inlet fluid velocity was increased from 0.4 m/s at a constant acceleration of 16 m/s^2 . The critical velocity at which the biofilm streamer was broken up was calculated. Each simulation was stopped once any broken streamer reached the downstream end of the channel and we will only focus on cohesive failure of streamers within this

period. For the single isolated streamer, when the flow velocity reached 1.39 m/s, the breakup of the biofilm streamer occurred as seen in Figure 10a. For two streamers in parallel, the biofilm streamers started to breakup when the flow velocity reached 1.25–1.3 m/s depending on the distance between the two streamers (Figure S8A). The two streamers broke almost simultaneously at the same point when they were on the in-phase oscillation mode (Figure 10b). The corresponding critical flow velocity was around 1.25 m/s in this case. However, when the two streamers were on out-of-phase mode, those streamers broke at different timepoints. The locations of the breakup appeared to be random. For example, the one of the streamers broke slightly towards the tail. Shortly after that, another streamer broke up at the point towards the head (Figure 10c). Overall, the critical fluid velocity for parallel biofilm streamers breakup seemed to be positively correlated

FIGURE 9 Maximum oscillation amplitude of inline biofilm streamers with different spacing distance (h/L) at flow velocity of 0.4 m/s [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 10 The comparisons of cohesive failure of streamers for (a) a single streamer ($v = 1.39$ m/s). The breakup of two parallel streamers (b) on in-phase mode, where $l/L = 0.46$ ($v = 1.255$ m/s) and (c) on out-of-phase mode, where $l/L = 0.78$, the critical velocities to cause biofilm streamers to break were 1.25 m/s (top streamer) and 1.32 m/s (bottom streamer). The breakup of two tandem streamers (d) the critical velocity for upstream streamer breakup was 1.45 m/s, where $h/L = 1$ and (e) the breakup critical velocity for upstream streamer was 1.49 m/s, where $h/L = 2$ [Color figure can be viewed at wileyonlinelibrary.com]

to the spacing distance (Pearson's correlation coefficient = 0.7 ; - Figure S8A). For two streamers in tandem, the upstream streamers always broke first because they were subjected to higher fluid shear forces. The cohesive failure seems taking place slightly towards the head or slightly towards the tail. For the former, the detached streamer segment would impinge into the downstream streamer which caused almost the entire downstream biofilm to break (Figure 10d). For the latter, the detached streamer segment moved away and the downstream streamer could keep oscillating with the flow (Figure 10e). As illustrated in figure S8B, when the spacing distance is less than $1.25 L$, the critical flow velocity to cause cohesive failure of the upstream streamer seemed to decrease with the gap. However, this threshold value remained around 1.5 m/s when further increase of the spacing distance.

5 | CONCLUSIONS

In this study, CFD-DEM models have been developed to predict oscillation of biofilm streamers with different configurations in uniform inlet fluid flows. For the single biofilm streamer, the biofilm streamer oscillation predicted by our computational modelling agreed well with the experimental measurements (Stoodley et al., 1998). 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 the biofilm streamer is influenced by its length and the flow velocity.

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

With the further increase of fluid velocity, the cohesive failure of biofilm occurred. For the streamers in parallel, the critical velocity slightly increased with the gap distance between two streamers. For streamers in tandem, the upstream streamer always broke first. If the first streamer broke towards the head, the detached streamer segment caused the downstream streamer to break. Otherwise, the detached streamer segment from the upstream streamer had little effect on the downstream streamer.

In future, it will be interesting to gain better understanding of biofilm streamer break-up for streamers with different mechanical properties and arranged in different configurations. It will also be interesting to consider other viscoelastic models to represent different biofilms. If the biofilms may undergo large deformation, we would also need to consider the nonlinear viscoelasticity of biofilms (Jana et al., 2020; Xia et al., 2018).

This model can be potentially up-scaled spatially by choosing appropriate sizes for particles (super-particles) and reasonable number of particles to represent biofilms in more complex environments, such as water filtration with micro-channels. This model could also be useful for the design of feed spacer meshes of membrane systems for water treatment and soil-like porous materials so that biofilm formation can be controlled.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

All authors contributed to this study. Yuqing Xia, Pahala G. Jayathilake, Bowen Li, Paolo Zuliani, and Jinju Chen designed the research. Y.X performed the simulation work, acquired the data, and did data analysis. Pahala G. Jayathilake, Bowen Li, and Jinju Chen contributed to data analysis. Pahala G. Jayathilake, Bowen Li, and Jinju Chen prepared the original draft. All authors reviewed and edited the manuscript. All authors have given approval to the final version of the manuscript.

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