Simulation of turbulence and dissolved oxygen concentration profiles over biofilm using $k-\varepsilon$ turbulence model

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Abstract The objective of this study is to investigate the flow structure over biofilm experimentally and theoretically. Velocity and turbulence profiles over biofilm measured by a laser Doppler velocimetry were compared to simulated profiles using the $k-\varepsilon$ turbulent model. Also, dissolved oxygen concentration profiles over biofilm are measured using a micro DO sensor. The $k-\varepsilon$ turbulence model was proved to be a useful tool for the understanding of mass transfer inside and outside biofilm. Dissolved oxygen concentration profile inside and outside biofilm showed the existence of turbulent diffusion inside biofilm.

Keywords $k-\varepsilon$ turbulence model; micro-DO sensor; turbulent diffusion

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Introduction

Biofilms are often of irregular porous morphology with filaments waving in flow causing turbulent diffusion not only outside biofilms but also inside biofilms. The mass transfer mechanism to such biofilm is influenced by flow structure over the biofilm, which is very complicated and has not been well understood so far.

Much research has been conducted concerning mass transfer mechanism in biofilms considering turbulent flow and turbulent diffusivity. Fluttering of nitrifying biofilms grown at a turbulent flow condition and an increase in biofilm activity with turbulence were reported by Nagaoka and Ohgaki (1988). Kugaprasatham *et al.* (1991) investigated the effect of turbulence on nitrifying biofilms and proposed a turbulent diffusion biofilm model considering turbulent diffusivity in a fluttering biofilm. Nagaoka *et al.* (1995) proposed a mathematical model to describe mass transfer mechanism into biofilms considering turbulent structure over biofilms. Nagaoka *et al.* (2003) adopted the $k-\varepsilon$ turbulence model to oscillatory flow over biofilms and successfully simulated the velocity profile.

The objective of this study is to investigate the flow structure over biofilm experimentally and theoretically. Measured velocity and turbulence profiles over biofilm were compared to simulated profiles using a $k-\varepsilon$ turbulent model. Also, dissolved oxygen concentration profiles over biofilm are measured using a micro-DO sensor, the profiles of which were compared with simulated profiles calculated using the $k-\varepsilon$ turbulent model considering turbulent diffusion.

Materials and methods

Velocity and turbulence measurement

A vertically flowing channel as is shown in Figure 1 was used for velocity measurement over biofim. Glucose was used as a main organic substrate for biofilm. Velocity of the channel was set at about 20 cm/s, under which biofilm was grown in the channel. Activated sludge was then seeded into the channels to start the experiment. Velocity in the channels at the decreased conditions was also measured changing circulating water flow rate. A fiber optic laser doppler velocimeter with back-scattering detection system was

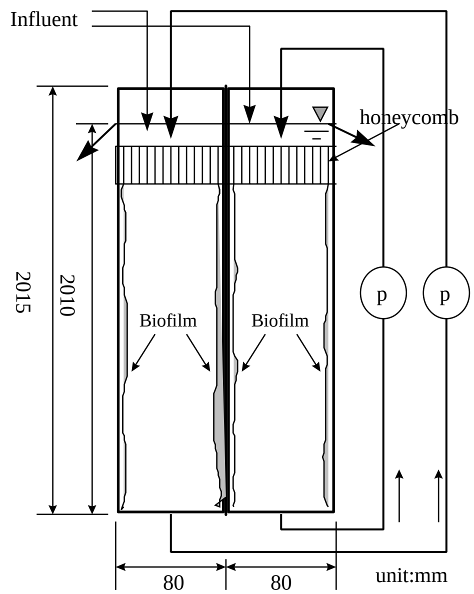

Figure 1 Experimental channel for velocity measurement over biofilm

used for the velocity measurements (Nezu and Rodi, 1986). Laser beams were transmitted through a transparent wall on which no biofilm grew. Velocity data were converted to digital data every 0.01 second through A/D converter and analyzed in a personal computer thereafter. Measurement time was 40 seconds.

DO profile measurement

Figure 2 shows an open channel for DO profile measurement. Substrate, whose main component was glucose, was fed to the channel. Channel water was circulated by a pump. A micro-DO sensor was set at the middle of the channel to measure DO profile outside and inside the biofilm attached on the channel bed. Temperature was set at 26 degrees and water depth was 3.5 cm. Circulation velocity was controllable by circulation pump flowrate.

Turbulent flow simulation

$k-\varepsilon$ model

For the calculation of turbulent flow over the biofilm, the biofilm surface was regarded as a smooth surface for simplicity. Low Reynolds number $k-\varepsilon$ model of Jones–Launder's type model (Jones and Launder, 1973) was employed for the simulation, the equation of

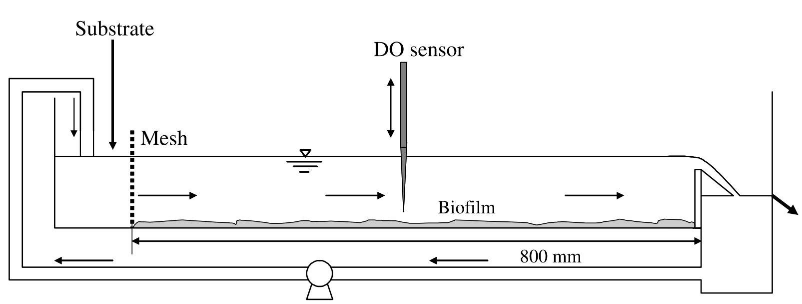

Figure 2 Experimental setup for the measurement of DO concentration profile inside and outside biofilm

which is shown as follows:

$$\frac{\partial}{\partial y}\left\{(\upsilon+\upsilon_t)\frac{du}{dy}\right\}=\frac{1}{\rho}\cdot\frac{dp}{dx} \tag{1}$$

$$\frac{\partial}{\partial y}\left\{\left(\upsilon+\frac{\upsilon_t}{\sigma_k}\right)\frac{\partial\varepsilon}{\partial y}\right\}+\upsilon_t\left(\frac{\partial u}{\partial y}\right)^2-\varepsilon+D=0 \tag{2}$$

$$\frac{\partial}{\partial y}\left\{\left(\upsilon+\frac{\upsilon_t}{\sigma_e}\right)\frac{\partial\varepsilon}{\partial y}\right\}+C_{\varepsilon 1}\frac{\varepsilon}{k}\left\{f_1\upsilon_t\left(\frac{\partial u}{\partial y}\right)\right\}-C_{\varepsilon 2}f_2\frac{\varepsilon^2}{k}+E=0 \tag{3}$$

$$\upsilon_t=C_\mu f_\mu\frac{k^2}{\varepsilon} \tag{4}$$

where ν: kinetic viscosity, ν_t: eddy kinetic viscosity, u: velocity, k: turbulent energy, ε: dissipation rate, y: distance from the wall. The values and forms of the parameters in the equations were determined as follows:

$$\left.\begin{aligned}&C_\mu=0.09,\ C_{\varepsilon 1}=1.55,\ C_{\varepsilon 2}=2.00,\ \sigma_k=1.00,\ \sigma_e=1.30,\\ &f_\mu=\exp(-2.5(1+R_t/50)),\ f_1=1.0,\ f_2=1-0.3\exp\left(-R_t^2\right),\\ &D=2\upsilon\left(\frac{\partial\sqrt{k}}{\partial y}\right),\ E=2\upsilon\upsilon_t\left(\frac{\partial^2 u}{\partial y^2}\right)^2\end{aligned}\right\} \tag{5}$$

where R_t is the turbulence Reynolds number defined as $R_t=\mathrm{k}^2/\nu/\varepsilon$. Boundary conditions for the equations were determined as follows:

$$\left.\begin{aligned}&u=k=\varepsilon=0 \quad \text{at the biofilm surface}\\ &\frac{\partial u}{\partial y}=\frac{\partial k}{\partial y}=\frac{\partial\varepsilon}{\partial y}=0 \quad \text{at the centre of the channel}\end{aligned}\right\} \tag{6}$$

The equations were transformed to dimensionless forms using $\bar{u}$ (cross-sectional mean velocity of the water channel) as a representative parameter of velocity and $D/2$ (half of the water-flowing channel width) as a representative parameter of length and solved numerically by the finite differential method (Kotake and Hijikata, 1988).

Calculation of DO profile

DO concentration profile over biofilm was calculated considering the turbulent diffusivity profile over the biofilm. Regarding the value of turbulent diffusivity as equal to that of kinetic viscosity, the following equation concerning DO concentration was solved numerically assuming DO concentration at the surface and the value of DO flux, J.

$$\upsilon_t\frac{dC}{dy}=J \tag{7}$$

where C: DO concentration, J: DO flux at the surface of the biofilm.

Results and discussion

Velocity and turbulence

Figure 3 shows examples of measured (plot) and calculated (line) velocity profiles above the biofilm with different Reynolds number. Biofilm thickness was 5 mm. The measured profiles are simulated very well by the model employed, where the biofilm surface was regarded as a smooth surface.

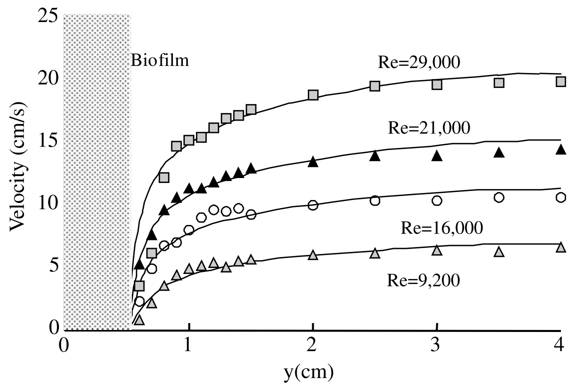

Figure 3 Measured (plot) and calculated (line) velocity profiles above the biofilm with different Reynolds number

Figure 4 shows measured (plot) and calculated (line) turbulent intensity profiles above the biofilm, the condition of which was the same as that of Figure 3. Although the measured values were larger than the calculated values, it is shown that the pattern of the measured profiles was well simulated by the model, the curves of which show exponential-type increase approaching to the surface and maximum values near the biofilm surface. The differences in the calculated and the measured values might be attributed to the influence of the inlet to the channel, which produced turbulence and was not far apart enough from the velocity measurement points for the produced turbulence to be dissipated.

Figure 5 shows calculated profiles of kinetic viscosity, which is related to turbulent diffusivity concerning mass transfer to the biofilm. The figure shows that as the Reynolds number increases, the intensity of mass transfer from bulk flow to the biofilm increases especially in the region close to the biofilm surface, which influences the mass transfer to the biofilm. It is suggested that the increase of Reynolds number increased the mass transfer rate to the biofilm thereby increasing the substrate uptake rate by the biofilm.

DO profile

Figure 6 shows measured and simulated DO profile inside and outside a biofilm, the thickness of which was 4 mm on average, changing velocity of flow over the biofilm. For the simulation of DO profile, profile of kinetic viscosity for Re = 16,000 and 29,000 (Figure 5) was used for the two cases. DO flux at the biofilm surface was assumed to be

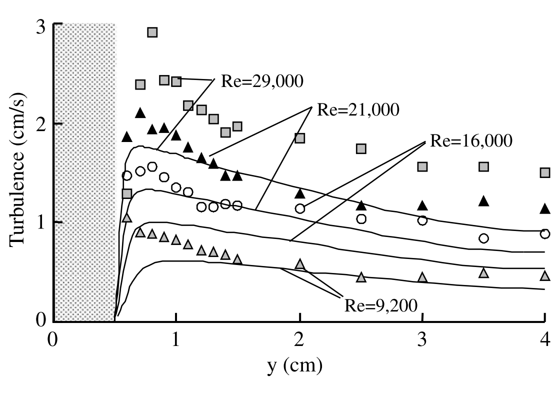

Figure 4 Measured (plot) and calculated (line) turbulent intensity profiles above the biofilm with different Reynolds number

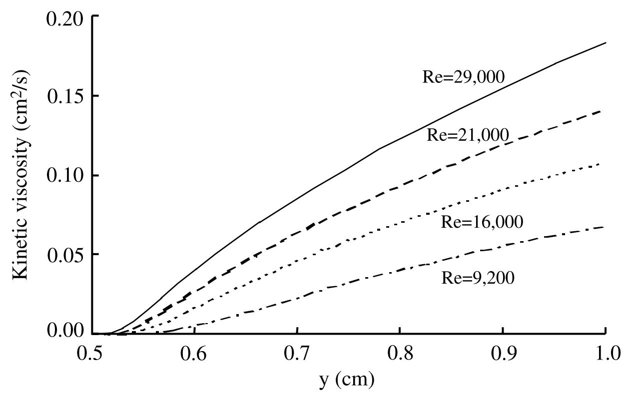

Figure 5 Influence of Reynolds number on kinetic viscosity profile above the biofilm

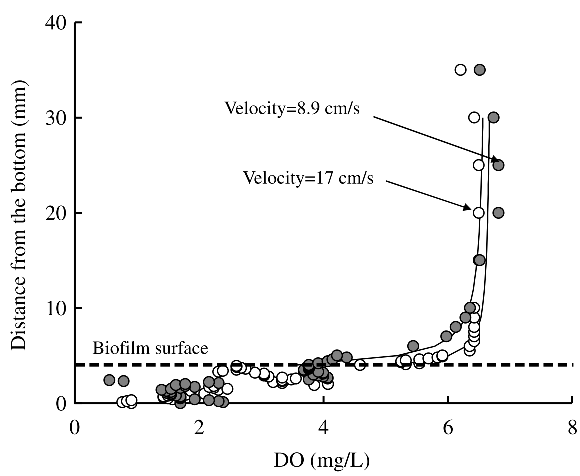

Figure 6 Measured and simulated DO profile inside and outside a biofilm, the thickness of which was 4 mm on average

0.00015 mg cm L^{-1} s^{-1} and 0.00040 mg cm L^{-1} s^{-1} for the two cases. In the 8.9 cm/s-velocity case, DO concentration profile over the biofilm shows milder gradient compared with that of 17 cm/s-velocity case. Also it is shown that the simulated curves are in good agreement with the measured profiles suggesting that the $k-\varepsilon$ turbulence model is a good tool for simulation of DO concentration profiles.

Conclusions

Velocity profile over biofilm was simulated well by $k-\varepsilon$ turbulence model showing availability of the turbulence model for the simulation of mass transfer over biofilms. Dissolved oxygen concentration profile outside biofilm measured with a micro DO sensor was in good agreement with simulated profiles using k-ε turbulence model.

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