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Dynamic behavior of bubble forming at capillary orifice in methane oxidizing bacteria suspension

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ABSTRACT

In this work, the dynamic behavior of bubble forming at capillary orifice was investigated using a developed bioreactor with methane oxidizing bacteria suspension as well as the movement and adsorption of microorganism at the gas-liquid interface were observed experimentally. The effect of gas flow rate from 0.8 to 1.45 mL/min on bubble formation evolution and departure process as well as the variations of equivalent departure diameter, departure volume and departure time of the leading bubble and the trailing bubbles were also explored during successive bubble formation. The experimental results showed that the chemotaxis effect and bubble expansion affected the movement and adsorption of microorganism at the gas-liquid interface, decreasing equivalent departure diameter and departure volume of the leading bubble as well as inrush number of the trailing bubble, shortening departure time of the leading bubble and inrush time of the trailing bubble, and prolonging waiting time of the leading bubble. Moreover, the increase of gas flow rate from 0.8 to 1.45 mL/min contributed to the increase of inrush number of the trailing bubble and the decrease of departure time of the leading bubble, but equivalent departure diameter and departure volume of the leading bubble were not much different under various gas flow rates. In addition, the trailing bubble merged into the leading bubble resulted in a significant fluctuation at the gas-liquid interface, affecting the bubble dynamic behavior and improving the mass transfer of gas mixture. These findings are beneficial to enhance the performance of the bioreactor by the optimal design of aeration system for bioconversion of methane fed into methane oxidizing bacteria suspension.

1. Introduction

Methane, as an important greenhouse gas, has an about 25 times greater global warming potential than carbon dioxide on a mass-basis over a century [1–4]. For this reason, many researchers have paid their attention to the studies of methane mitigation technology all over the world [5–8]. Among these methane mitigation techniques being explored, methane bioconversion by methane oxidizing bacteria is regarded as a more reasonable method due to its environmental friendliness and the ability to produce liquid fuel as well as the stably operation characteristic at ambient temperature and pressure without the additional energy consumption [9–12]. Usually, methane oxidizing bacteria are cultivated in bioreactors, which can be typically divided into suspended-cell and immobilized-cell [13–15]. Currently, compared to the immobilized-cell bioreactors, the suspended-cell bioreactors are widely employed for methane bioconversion because of their good mass transfer [16–18]. During methane bioconversion process, the gas mixture containing methane and oxygen is commonly supplied from the bottom of the suspended-cell bioreactor via a gas distribution device, forming bubbles. And then, the methane and oxygen diffuse from the bubbles via the gas-liquid interface and medium solution into methane oxidizing bacteria for theirs growth by methane bioconversion. In this case, the growth and department of bubbles from capillary orifice of the gas distribution device induce the bubble flow in methane oxidizing bacteria suspension, so the bubble dynamic behavior can impact the mass transfer of methane and oxygen as well as the movement and distribution of methane oxidizing bacteria in biological suspension, subsequently affecting the cell growth and biochemical degradation performance [19,20]. Therefore, it is necessary to understand the dynamic behavior of bubble forming at capillary orifice in methane oxidizing bacteria suspension.

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In the past decades, many studies on the bubble dynamic behavior in water or other liquid have been widely reported [21–26]. Zhu et al. [21] used a high-speed visual system for investigating the bubble growth and departure in stagnant water, and the experimental results showed that the bubble growth process experienced three stages, including the initial growth, the speed-up growth, and the speed-down growth. Liao et al. [22] experimentally investigated the bubble growth and departure at the tip of inclined glass capillary tubes, and the visual experiment revealed that the bubble growth experienced a sphere-like growth stage and the asymmetric growth stage at the tip of an inclined capillary tube. Xie et al. [23,24] explored the bubble formation and detachment dynamics in stagnant liquid by visualization experiment, and discussed the bubble evolution features. Di Bari and Robinson [25] studied the growth mechanism of adiabatic gas bubble from submerged orifices and elucidated the interdependence of the bubble shape and the pressure field during the bubble growth and departure. Vafaei [26] surveyed the triple line and bubble growth dynamics in water, gold, silver and alumina nanofluids. In recent years, the researches on bubble dynamic behavior in biological suspension have been carried out. Ding et al. [27,28] visually investigated the bubble dynamic behaviors and observed the influence of inlet concentration, blast orifice size and gas flow rate on the distribution and growth of microalgae. Zhao et al. [29,30] examined the dynamic behaviors of bubbles coalescing at two parallel capillary orifices and analyzed the movement and distribution of microalgae at the gas-liquid interface. As mentioned above, existing works have explored the bubble dynamic behaviors in different fluids. However, to date, the dynamic behavior of bubble including gas mixture as substrate for the microorganism growth in the suspended-cell bioreactor has been rarely reported, and the different bubble dynamic behaviors caused by special physical properties, biochemical reactions and adsorption characteristics of microorganism at the gas-liquid interface have not been well understood in methane oxidizing bacteria suspension.

In this work, a bioreactor with methane oxidizing bacteria suspension is developed to observe the movement and adsorption of microorganism at the gas-liquid interface and the bubble dynamic behaviors in the suspension and pure water. Moreover, the effect of gas flow rate from 0.8 to 1.45 mL/min on bubble formation evolution and departure process is explored. In addition, the variations of equivalent departure diameter, departure volume and departure time of the leading bubbles and the trailing bubbles are also discussed during successive bubble formation.

2. Materials and methods

2.1. Microorganism and cultivation

The employed microorganism was *Methylosinus sporium* (DSMZ 17706), methane oxidizing bacteria, which was purchased from DSMZ. *Methylosinus sporium* was cultivated in the mineral salt medium (MSM), which contained the following elements (g/L): $Na_2HPO_4 \cdot 12H_2O$, 6.15; KH_2PO_4, 1.52; $MgSO_4 \cdot 7H_2O$, 0.2; $CaCl_2 \cdot 2H_2O$, 0.05; $NaNO_3$, 2.6 and 10 mL/L of a trace element solution composed of (g/L) EDTA, 0.5; $FeSO_4 \cdot 7H_2O$, 0.2; $ZnSO_4 \cdot 7H_2O$, 0.01; $MnCl_2 \cdot 4H_2O$, 0.003; H_3BO_3, 0.03; $CoCl_2$, 0.011; $CuCl_2 \cdot 2H_2O$, 4.43; $NiCl_2 \cdot 6H_2O$, 0.002; $Na_2MoO_4 \cdot 2H_2O$, 0.003. The pH value of culture medium was adjusted to 7.0 using 0.1 M NaOH/HCl.

2.2. Experimental system

As shown in Fig. 1, the bioreactor developed in this work was a vessel with the height of 200 mm, the length of 100 mm and the width of 20 mm, which was fabricated by polymethyl methacrylate (PMMA). The gas mixture with methane volume fraction of 50% as the optimum value for methane bioconversion was obtained by mixing methane with oxygen in a collecting bag. During the working process, the methane oxidizing bacteria suspension at an initial optical density (650 nm) of 0.06 was inoculated into the bioreactor and the height of the suspension was maintained at 60 mm. And then, the gas mixture stored in a syringe of 20 mL was injected into the bioreactor by a syringe pump (LSP02-1B, China) through a glass capillary with the inner diameter of 0.1 mm and the length of 50 mm, which located at the bottom of the bioreactor.

2.3. Analysis methods

The dynamic behavior of bubble forming at capillary orifice in methane oxidizing bacteria suspension was captured by the data acquisition system consisting of a high speed camera (Mikrotron, Germany) and data storage system. The captured images of bubble were processed and analyzed by Matlab and Photoshop software. The initial optical density of methane oxidizing bacteria suspension was determined by a UV–visible spectrophotometer (UV1600, China) and the pH value of culture medium was measured by a pH meter (Mettler-Toledo, China) calibrated using buffers (pH of 4.0 and 7.0). The gas flow rate was determined by a gas mass flow controller (FMA-2600A Series, Omega Engineering Inc.). All data were repeated more than ten times.

3. Results and discussion

3.1. Movement and adsorption of microorganism

In this work, the movement and adsorption of microorganism at the gas-liquid interface were investigated because they can be considered as critical factors affecting the surface tension of methane oxidizing bacteria suspension and the mass transfer of methane as carbon source for microorganism growth, changing the bubble dynamic behavior. Fig. 2 shows the movement and adsorption of microorganism at the gas-liquid interface during the growth process of bubble forming at capillary orifice. It can be seen that a large number of microorganism cells and bacterial colonies were enriched at the gas-liquid interface. This behavior can be explained by the fact that methane as the sole carbon source was diffused from bubble via the gas-liquid interface into medium solution, causing the movement of microorganism cells and bacterial colonies in the suspension toward the gas-liquid interface with higher methane concentration due to the chemotaxis effect. For bubble containing methane fixed in the bioreactor with methane oxidizing bacteria suspension, in our previous work, it had been also found that the chemotaxis effect as the single factor can drive a large number of microorganism cells and bacterial colonies toward the gas-liquid interface. Under such circumstances, these microorganism cells and bacterial colonies reached near the gas-liquid interface, which can be captured by capillary force and subsequently enriched on the bubble surface. Moreover, the capillary force can also capture these microorganism cells and bacterial colonies, which collided with the bubble surface during the expansion process of the gas-liquid interface caused by the bubble growth. In addition, some of microorganism cells and bacterial colonies were carried by the movement of the suspension with the streamline of the gas-liquid interface expansion. In this case, these microorganism cells and bacterial colonies moving near the gas-liquid interface can be captured by capillary force and adsorbed on the bubble surface. Therefore, it can be obtained in this work that the chemotaxis effect and the bubble expansion as two crucial fac-