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Hydrodynamics and permeability of aerobic granular sludge: The effect of intragranular characteristics and hydraulic conditions

Kai Pan[a], Kuizu Su[a,*], Shuai Zhang[a], Zehui Sun[b], Deqian Xu[a], Shaogen Liu[c]

[a] School of Civil Engineering, Hefei University of Technology, Hefei 230009, PR China
[b] College of Electrical Engineering and Automation, Anhui University, Hefei 230601, PR China
[c] School of Environment and Energy Engineering, Anhui Jianzhu University, Hefei 230601, PR China

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ABSTRACT

Aerobic granulation technology has been widely investigated for its efficient treatment of municipal and industrial wastewater. The efficiency and stability, which are affected by the permeability and forces on granule surface, are both crucial to its full scale application. In this work, the structural and hydrodynamic characteristics of the granules were investigated using experimental approach and numerical simulations. Aerobic granule was considered to be a porosity sphere composed of smaller particles. Mixture model in FLUENT was used for gas-liquid two-phase flow simulation, and the phase resistance was calculated using schiller-naumann function. The influence of gas holdup and granule size on the surface force was simulated and the results show that the shear stress increases with the gas holdup, while the granule size has little effect on the surface force. Using the computational fluid dynamics (CFD) numerical model, it was demonstrated that the convection path lines for the granules colored by the velocity magnitude increase with the Reynolds number and the primary particle diameter. The model also indicated that improving the permeability of a granule can reduce the total pressure on the granule surface, but it has less effect on the strain rate. In addition, a new simulation was developed to evaluate the fluid collection efficiency, which proved to be in good agreement with the results determined by formulas and experiments.

1. Introduction

Compared with activated sludge flocs, aerobic granules have many advantages when employed for municipal and industrial wastewater treatment, such as regular shapes, densities, strong microbial structures, and good settling abilities [1–3]. These advantages are due to their highly porous, permeable and compact structure that they develop as a result of the high shear stresses surrounding them. Accordingly, there are obvious internal convective flows in the granules resulting from their porous structures [4,5].

The permeability of aerobic granules affects their settling velocity and mass transfer [6–8]. Through accurate settling experiments and comparing the ratio of theoretical and experimental velocity, the permeability factor and hydraulic permeability can be calculated. In addition, the fluid collection efficiency may be used to estimate the permeability of granules more directly [4,9].

Aerobic granules are fractal-like aggregates that are composed of small particles [10–12]. For accurate computations, a fractal dimension geometry has been established to define these frail structures to promote the understanding of their influence over a wide array of granulation phenomena, such as turbulence, shear abrasion and fluid kinetics [13].

The forces on the granule surface, including the hydrodynamic shear force and total pressure, primarily affect their formation, structure and stability. The hydrodynamic shear force can be a result of gas or liquid flows or particle on particle collisions in a Sequencing Batch Reactor (SBR). The granules tend to become porous and have a weaker structure when the shear force is weak [14]. The total pressure includes the static and dynamic pressures, and is the main component of the force acting on the granules in the SBR. But there is still little knowledge of the effect that the total pressure has on the granular surface.

Computational fluid dynamics (CFD) has received increasing attention as a powerful simulation tool to investigate the hydrodynamic behavior of granules. Díez et al. carried out experiments using a particle image velocimetry technique and CFD method to analyze the shear strain rate and the relative velocity between

* Corresponding author.
E-mail address: sukz@hfut.edu.cn (K. Su).

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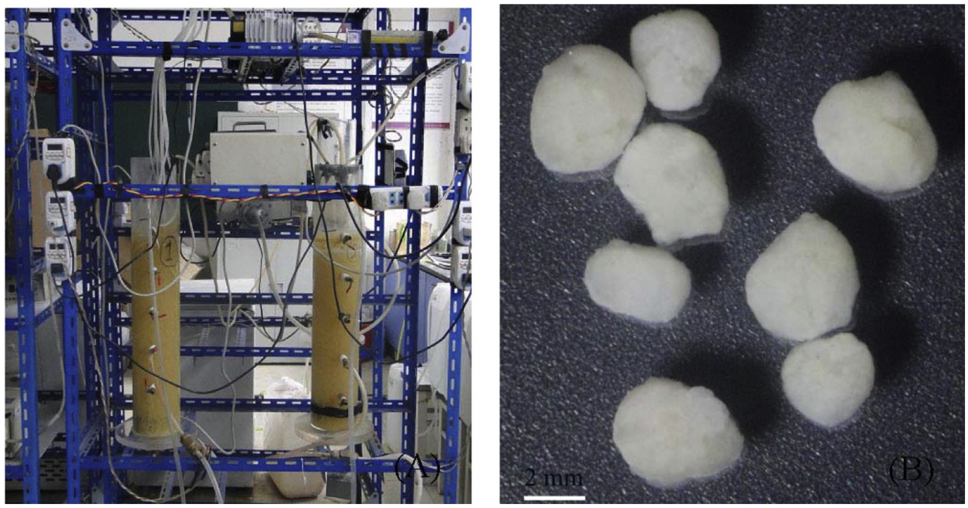

Fig. 1. Images of the sequential batch reactors (A) and the aerobic granules (B).

the water and the granules in SBR [15]. The influence of the non-homogeneous structure of a permeable sphere on the flow field was investigated for low to medium- large Reynolds number conditions [16]. Liu et al. simulated the flow field surrounding a single granule, which demonstrated that the velocity in the granule and the strain rate on the granular surface significantly depended on the permeability and the Reynolds number [5]. The hydrodynamic properties of fractal aggregates in a flow field were simulated using three-dimensional CFD [17]. However, information on the hydrodynamic behavior and permeability of aerobic granules at different hydraulic conditions in SBRs is still limited.

In this paper, the porosity, fractal dimensions and permeability of granules were collected from experiments. Then, the fluid dynamics behavior of the granules was analyzed using CFD modeling approach. A new simulation was developed to evaluate the fluid collection efficiency. The hydrodynamics of an individual granule is essential for the stability of aerobic-granule-based reactors and the successful operation of wastewater treatment systems.

2. Materials and methods

2.1. Experimental setup

As shown in Fig. 1A, a lab-scale column (65 cm high and 10 cm in diameter) with a working volume of 4.3 L was used to cultivate aerobic granules. Air was introduced through a diffuser with an air pump at the bottom of the reactor, and the airflow rate was controlled via a gas-flow controller. The seed sludge was taken from an aeration tank in the Wangxiaoying Municipal Wastewater Treatment Plant, Hefei, China. The seed sludge had a mixed liquor suspended solid (MLSS) concentration of 3–4 g/L and a sludge volume index (SVI) of 129 mL/g. The reactor was operated sequentially: 10 min of influent filling, 240 min of aeration, 20 min of setting and 5 min of effluent withdrawal.

The reactor was fed with an artificial wastewater containing sucrose, NH_4Cl and NaH_2PO_4. The soluble chemical oxygen demand (COD) and total nitrogen (TN) concentrations were 0.5–1 g/L and 0.025-0.08 g/L, respectively. The wastewater composition was added to ensure the ratio of BOD to N to P was 100:5:1. In addition, elements were added, which contained $MgSO_4 \cdot 7H_2O$ 50 mg/L, $FeCl_3 \cdot 6H_2O$ 0.83 mg/L, $CaCl_2$ 20 mg/L and the micro-elements. The influent pH value was adjusted to 7.5 ± 0.1 by the addition of Na_2CO_3. The temperature of the reactor was maintained at 25 ± 1 °C using a belt heater and a temperature controller. The aerobic granules collected from the SBR are shown in Fig. 1B.

2.2. Analytical methods

The size of aerobic granules was measured using an image analysis system (Motic Images Advanced) with an Olympus CX41 microscope and a digital camera (sonyDSC-HX1, Japan). The granules were dried in an oven at 101 °C for 2 h, and the dry mass of the granules was weighed on an analytical balance (OHAUS, CP214). The density of the granules was determined according to the method used by Zheng et al. [18]. The ratio of the wet to dry mass of the granules was estimated to be 3.45 according to the method used by Li and Yuan (2002). The COD, MLSS, SVI, and specific gravity were determined following the Standard Methods [19].

3. Theory

3.1. Assumptions and governing equations

In the CFD modeling, the aerobic granule is assumed to be a homogeneous-structured permeable sphere with diameter d_a and radius r_a. The granule moves at a steady speed (u) through an incompressible Newtonian fluid with viscosity (μ_f) and density (ρ). The model (shown in Fig. 2) is similar to that employed by Liu et al.

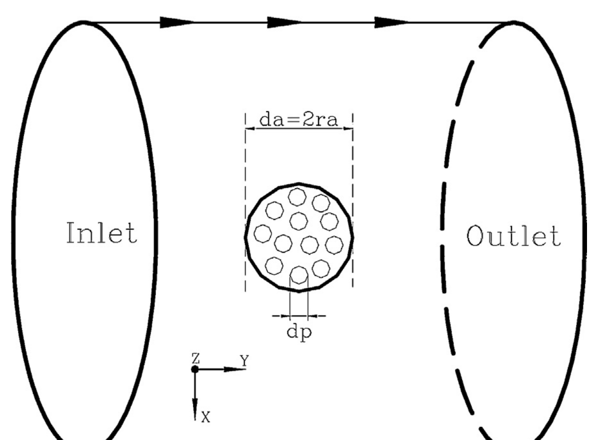

Fig. 2. Schematic of the physical system used in the computations.