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Structural characteristics of a spiral symmetry stream anaerobic bioreactor based on CFD

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ABSTRACT

The structural characteristics of a spiral symmetry stream anaerobic bioreactor (SSSABR) contribute to its super-high-rate performance. This study investigated the structural characteristics of SSSABR, including distribution zone, spiral reaction zone, and three-phase separation zone, by computational fluid dynamics (CFD). In distribution zone, uniformity and hydraulic head loss increased with increasing number of orifices, and five-orifice is deemed optimal for distributor. In spiral reaction zone, a 45° cutting angle produced a tangential velocity strong enough to spin the granular sludge and maintain a moderate mixing intensity. A 30° installation angle produced a wide range of spiral flows. The 120° symmetrical arrangement of plates formed a strong–weak periodic spiral flow that strengthened material exchange. In separation zone, a value of 0.625 for the frustum characteristic parameter i ($i = r_1/r_2$, where r_1 presented the bottom frustum radius of reverse cone, and r_2 presented radius of spiral reaction zone of SSSABR) provided moderate recirculation. The relative error of dead zone rate between CFD and tracer experiment was 4.66%.

1. Introduction

The anaerobic bioreactor (ABR) is an important tool for wastewater processing because of its convenience in operation, technological maturity, and dual resolution of environmental pollution and energy shortage [1–3]. Therefore, it has attracted widespread interest from scholars and shown good potential for industrial development [4]. One of the most broadly used ABRs worldwide is the upflow anaerobic sludge bed reactor (UASBR) [4], which employs a three-phase separator to separate sludge retention time (SRT) and hydraulic retention time (HRT) [1]. The organic loading rate (OLR) of the UASBR ranges from 4 to 8 kg/(m^3·d) of chemical oxygen demand (COD) [5,6]. In the 1980 s, the internal circulation reactor (ICR) was invented to create a reactor with two-stage three-phase separators [7] with an OLR of 20 kg COD/(m^3·d) [4,8]. Later, Bachmamn developed the anaerobic baffled reactor (ABR) by installing a series of vertical baffles in the reactor; the OLR reached 28 kg COD/(m^3·d) [9–11].

Recently, a spiral symmetry stream anaerobic bioreactor (SSSABR) was invented by Xiaoguang Chen that employed a semi-elliptical internal component [12]. Featuring a super-high-rate performance, the OLR reached 361.5 kg COD/(m^3·d) which is 45 times that of the UASBR[13]; the mean coefficient variation value (in terms of the removal efficiency, adsorption property, settling ability, flocculability) was 0.67 times that of the UASBR[14]; the impact of gas on the axial dispersion for the SSSABR was much smaller than for the UASBR[15]; the reactor was applied to treat azo dyes wastewater[16]. Apparently the structural characteristics of the SSSABR contribute to its performance enhancement and for this reason its structural characteristics needs to be investigated.

In the past, two approaches were adopted to investigate reactor structures: semi-empirical experiments and theoretical analyses. However, the semi-empirical experimental approach often involved heavy workload, high operational costs, and various problems when enlarging the models, and hence the effects of a design were not very instructive. Theoretical analyses can give clear and typical information in the form of formulas, but they are limited to dealing with simple structures and physical phenomena, hence applications were limited. With the development of computational fluid dynamics (CFD), an efficient, economical and time-saving tool for researching the structure of reactors appeared [17]. CFD

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Nomenclature

α	Volume fraction (%)
ρ	Density ($kg\ m^{-3}$)
ν	Velocity ($m\ s^{-1}$)
μ	Viscosity (Pa s)
ε	Turbulence dissipation rate of specific phase ($m^2\ s^{-2}$)
μ_t	Turbulence viscosity (Pa s)
σ_k	Turbulent Prandtl number for kinetic energy
σ_ε	Turbulent Prandtl number for rate of energy dissipation
t	Time (s)
p	Pressure (Pa)
g	Gravitational acceleration (9.81 $m\ s^{-1}$)
M	Interphase transfer force (N)
R	Interaction force (N)
K	Interphase momentum exchange coefficient
f	Drag function
d	Diameter (m)
Re	Reynolds number
k	Turbulence kinetic energy of specific phase ($m^2\ s^{-2}$)
G_k	Production of turbulent kinetic energy ($kg\ m^{-1}\ s^{-3}$)
C_μ	Coefficient for turbulence viscosity
$C_{1\varepsilon}$	Constants in the standard k- ε model
$C_{2\varepsilon}$	Constants in the standard k- ε model
x_d	Dead zone rate of cross-section (%)
h	Height of cross-section (cm)
d_r	Diametre of reaction zone (cm)
V	Volumn of reactor (ml)
$E(T)$	Residence time distribution density (min^{-1})
$C(T)$	Tracer concentration in effluent at the time of T ($10^{-2}mmol\ L^{-1}$)
$\overline{T}$	Average residence time (min)

Subscripts

i	Phase number
j	Phase number
m	Mixture

has gained popularity over traditional wastewater treatment modelling approaches, as it is a high precision technique allowing evaluation of the engineering systems, which are expensive, difficult or even dangerous to reproduce, and can save manpower and expenses, and shorten testing periods [18,19]. Meanwhile, CFD can make up for obscurities encountered with pure mathematical models used in theoretical analysis, and can visually reveal the actual fluid phenomena in the reactor through simulation visualization techniques. CFD has been widely and successfully used in the evaluations of the wastewater treatment systems [20,21].

In view of the above, the structural characteristics of the SSSABR, including its distribution zone, spiral reaction zone, and three-phase separation zone, were simulated using CFD software. Concurrently, a fluoride-ion tracer experiment was performed to verify the reliability of the CFD simulations [22].

2. Materials and methods

2.1. Experimental equipment

The schematic diagram of a SSSABR was shown in Fig. 1. With a total effective volume 6.0 L, the SSSABR was composed of a distribution zone, a spiral reaction zone, and a three-phase separation zone; the effective volume of each zone is 0.5 L, 4.5 L, and 1.0 L, respectively. Its configuration parameters were: distribution zone diameter 0.08 m and height 0.10 m, reaction zone diameter 0.08 m and height 0.96 m, separation zone height 0.30 m. The total height of reactor was 1.36 m. The upper and lower diameters of the three-phase separator were 0.12 m and 0.05 m, respectively. The spiral reaction zone was divided evenly into three chambers using three semi-elliptical plates (inner components). The gas generated from the anaerobic reaction was collected by exhaust pipes in the corresponding chambers under the semi-elliptical plates to reduce fluid flow disturbances. The reaction zone were provided with an insulation layer, in which the circulating hot water was heated by a digital water bath, in order to keep the temperature as 35 ± 1 °C in the reaction zone.

2.2. Method

2.2.1. Tracer

The correct choice of tracer was one of the key factors for the successful tracer test. In general, the tracer has the following characteristics: 1) similar physical characteristics when compared with the tested fluid so that it mixes easily; 2) accurately detectable; 3) is neither reactive nor volatile, and is neither precipitated nor adsorbed; and 4) is found in low concentrations in the tested waste water and sludge.

Taking into account these requirements, the tracer chosen for the experiment was sodium fluoride as the concentration of fluorine ions in wastewater is very low and is not assimilated as a nutrient by micro-organisms. In this experiment, the concentration of fluoride ion was 0.1 mol/L, and its volume was 5 ml; hence the total amount of NaF was 5×10^{-4} mol.

2.2.2. Operation

The experiment involved using a stimulus-response technique with pulses of specific time durations. Fluorine ions were injected instantaneously in the inflow as a tracer to form a pulse signal, and then the fluorine concentration in the effluent was sampled at periodic intervals. The method of determination adopted an ion-selective electrode that converts the activity of the fluoride ion to an electrical potential.

2.3. Computer and software

The simulations were run on a computer configured with a Intel (R) Core (TM) i5 CPU M 450 @ 2.40 GHz processor and 4.00 GB memory. For the simulations, we used Gambit 2.3.16, Exceed 13, and the Fluent 6.3.26 software package.

3. Numerical simulation model

3.1. Eulerian–Eulerian model

The Eulerian model is commonly used in multiphase systems, where momentum exchange between the phases is significant [23]. In this paper, a 3-D Eulerian-Eulerian three phase model was employed. The wastewater was defined as the primary phase, and the gas & sludge granules was defined as the second phase. Each phase was presumed to be incompressible in this study. The wastewater was assumed to have a dendity of 1050 kg/m^3 at 35 °C. The sludge granules took up about 10% of the volume in the reactor with the diametre of 1 mm, and the density was presumed 1460 kg/m^3. The gas bubbles were assumed to have a diamere of 0.1 mm with a density of 1.225 kg/m^3.