Characteristics of Inner Cycle Flow Rate in Internal Circulation (IC) Anaerobic Reactor under Different Conditions by Fluent Method

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Abstract. The process of gas-liquid two-phase flow of an IC anaerobic reactor (25L) was simulated by fluent software. Inner Cycle Flow Rate (QIC) under different volume loading rate(OLR), ratios of riser diameter to reactor diameter(Dr/D), ratios of reactor height to diameter (H/D) were investigated respectively. The results showed that: (i) When OLR was 17.28kgCOD/ (m^3•d), a maximum value of QIC (0.0099m^3/h) was reached under conditions of H/D (5), Dr/D (0.081). A empirical correlation of QIC and biogas production was gained by fitting analysis; (ii)When Dr/D was 0.081, a maximum value of QIC(0.0079m^3/h)was reached under conditions of OLR(11.52kgCOD/(m^3•d)), H/D(5); (iii)When H/D was 3, a maximum value of QIC(0.011m3/h) was reached under conditions of OLR(17.28kgCOD/(m^3•d)), Dr/D(0.081).

Introduction

Inner cycle flow rate (QIC) is one key issue for design and calculation of IC reactor. Pereboom[1] et al. proposed their calculation formula of QIC through an iteration procedure based on the principle of internal airlift reactor, however the process was rather complicated, error prone and time consuming.

Numerical simulation by Fluent is an important method on design and operation of biological reactor of wastewater treatment[2]. Recently, researchers make a series of studies on anaerobic reactors by this method[3].

Therefore fluent technology will be used to study 2-dimensional distribution of gas-liquid two-phase flow in an IC reactor, QIC under different OLR, Dr/D and H/D will be investigated in this paper. It is expected that it can provide much information for design and controlling operation of IC reactor.

Numerical simulation

Simulation object

The simulation was done in an IC reactor (volume 25L, height 0.691m, diameter 0.185m). A three-phase separator was mounted at 0.155m from top of the reactor. The equipment structure was shown in Fig. 1
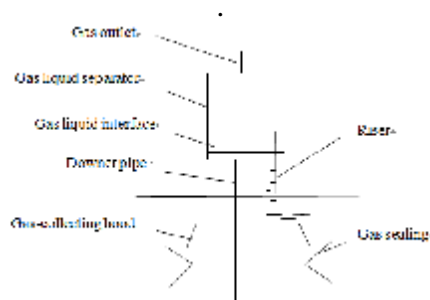

Fig. 1. Structural diagram of simulation object

Numerical Simulation Process

Continuity equation

The mixture momentum equation was modeled as:

$$\frac{\partial}{\partial_t}(\varphi_k \rho_k) + \nabla \cdot (\varphi_k \rho_k \nu_k) = 0 \tag{1}$$

Model parameters

The physical model was meshed with non-structured grid by CFD code fluent6.3 GAMBIT preprocessor program and grid-independence was validated. When the grid was implemented with a total number of 28230 cells, local gas holdup and upflow velocity in riser began to stabilize with increasing of grid numbers. At that moment it was sufficient to obtain independent result and meet the demand of computation precision.

The pressure-based solver was used in 2-dimension unsteady computational model. Time step size was equal to 0.0003. When all variable values was less than 1×10^{-3} and average rate of liquid in riser reached a constant value with increasing of time, solutions was convergent. The pressure-velocity coupling was obtained by using SIMPLEC algorithm; the first order upwind was performed to solve momentum equation, volume fraction equation and turbulent kinetic energy equation; a standard no-slip boundary condition was applied to all walls.

Boundary conditions: inlet was modeled with a velocity-inlet; top surface of reactor was modeled as pressure-outlet. All other solid surfaces were defined by wall boundary.

Initial conditions: liquid velocity was zero, gas volume fraction was 1.0 and others we reset as default values. Simulation object filled with water under air-water interface.

Operation conditions we selected was as follows: influent COD concentration was 4000mg/L, COD removal rate 95% and temperature 35℃. The selected ranges of simulation parameters were shown in Table 1.

Table 1 Selection range of parameters influent simulation

Inflow ($m^3 \cdot d^{-1}$)	OLR ($kgCOD \cdot m^{-3}d^{-1}$)	D_r/D	H/D
0.06	8.64	0.0032	3
0.07	10.08	0.0049	4
0.08	11.52	0.0065	5
0.09	12.96	0.0081	6
0.1	14.40	0.0097	7
0.11	15.84	0.114	/
0.12	17.28	/	/
0.13	18.72	/	/
0.14	20.16	/	/

Results and discussion

Relationship between QIC and OLR

OLR was one main parameter of IC reactor. Gas production increased with increasing of OLR, which bring about the change of Q_{IC}. When D_r/D and H/D was 0.081 and 5 respectively, Q_{IC} under different OLR value (8.64, 10.08, 11.52, 12.96, 14.40, 15.84, 17.28, 18.72, 20.16kgCOD/ $(m^3 \cdot d)$) were shown in Fig.2.
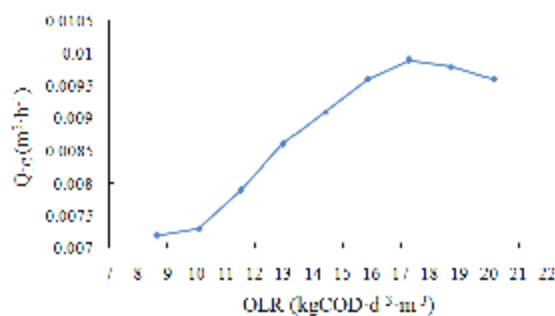
Fig. 2. Q_{IC} under different OLR

According to Fig. 2, it was shown that the Q_{IC} increased firstly and then declined with increasing of OLR. When OLR increased from 8.64kgCOD/ $(m^3 \cdot d)$ to 17.28kgCOD/ $(m^3 \cdot d)$, Q_{IC} reached the peak of 0.0099m^3/h. But when OLR increased to 20.16kgCOD/ $(m^3 \cdot d)$, Q_{IC} decreased to 0.0096m^3/h.

The reason of this phenomenon is that generally gas production was proportional to OLR in same reactor, so gas production and Q_{IC} increased with increasing of OLR initially, then turbulent and eddy current enhanced with increasing of circulation resistance. When density of mixture in riser decreased to a critical value, upward flow appeared fracture and then Q_{IC} decreased[4].

Correlation between QIC and biogas production

The results of Q_{IC} (Y) under different OLR (Fig. 2.) were shown in Table 2.

Table 2 Relationship between gas yield (X) and Q_{IC} (Y)

OLR (kgCOD·m⁻³d⁻¹)	X (L·h⁻¹)	Y by simulating (L·h⁻¹)
8.64	2.84	7.16
10.08	3.32	7.31
11.52	3.79	7.89
12.96	4.27	8.60
14.40	4.74	9.12
15.84	5.21	9.60
17.28	5.69	9.89
18.72	6.16	9.84
20.16	6.64	9.65

The correlation fitted between Y and biogas production (X) in Table 2 was as follow by fitting analysis:

$$Y=13.87-0.142X^3+1.8X^2-6.43X \tag{2}$$

According to above regression result, biogas of per cubic meter could lift 1.4~2.4m^3 liquid to three-phase separator. These were very in accordance with related experimental research and engineering practices, their results showed that biogas of per cubic meter could lift1~2m^3 liquid to three-phase separator.

Inner Cycle Flow Rate under different Dr/D

Related research[5] based on different riser diameters had shown that different gas-liquid mixing proportion could be adjusted by varying riser diameter appropriately, then density of mixtures could be maintained in a reasonable range and recycling process could be kept on.

When OLR and H/D was 11.52kgCOD/ $(m^3 \cdot d)$ and 5 respectively, Q_{IC} and average gas holdup in riser under different D_r/D value (0.032, 0.049, 0.065, 0.081, 0.097, 0.114) were shown in Fig. 3.
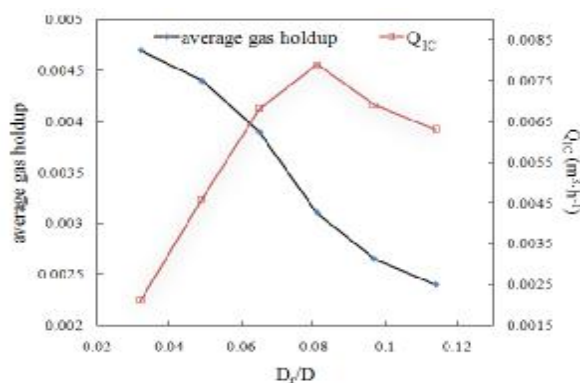
Fig.3. Average gas holdup in riser and Q_{IC} under different D_r/D

Fig. 3 showed that Q_{IC} increased from 0.0021m^3/h to 0.0079m^3/h with D_r/D increasing from 0.032 to 0.081. Then Q_{IC} decreased from 0.0079m^3/h to 0.0063m^3/h with D_r/D increasing from 0.081 to 0.114. The results indicated that the Q_{IC} increased firstly and then declined as flow area of mixture increased. Meanwhile average gas holdup in riser decreased from 0.0046 to 0.0024, when D_r/D was adjusted from 0.032 to 0.114. The reason of this phenomenon is that drag of internal circulation flow decreased and apart of gas was entrained in cycling by upward flow with increasing of Dr/D, which led that average gas holdup decreased gradually in riser[6]. When D_r/D was 0.081, Q_{IC} reach maximum value of 0.0079m^3/h. It means that recommended value of D_r in this reactor is 15mm.

Liquid velocity field under different H/D value (3, 5, 7) were shown in Fig. 4. Arrow direction represented moving direction of liquid and color represented velocity magnitude of liquid.
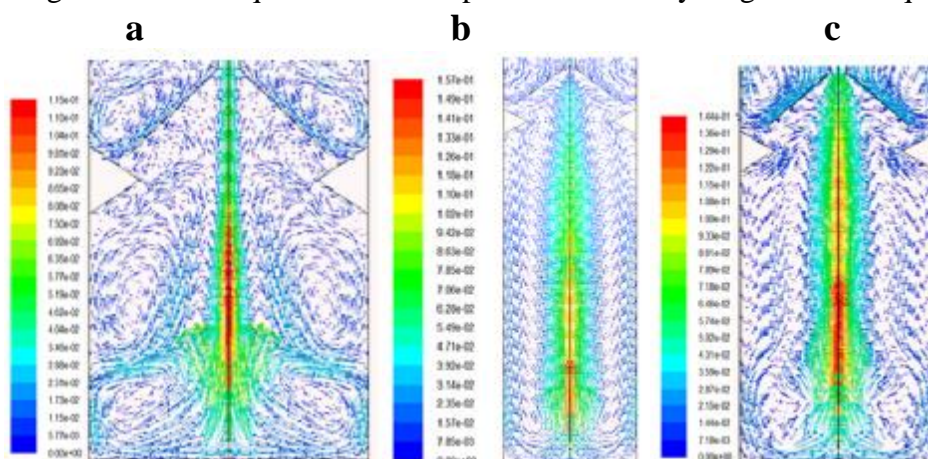

Fig.5 Liquid velocity vectors under different H/D. (a) H/D =3, (b) H/D =5, (c) H/D =7.

When H/D is 3, 5, 7 respectively, there were significant difference in characteristics of back mixing and liquid velocity in riser as shown in Fig. 4. Fig. 4a showed that two large vortexes formed at the bottom of the reactor and back mixing phenomenon was most observable which will be helpful to the hydraulic conditions in the reactor; Fig. 4b showed that two weaker vortexes formed and weaker back mixing was found; Fig. 4c showed that weakest vortexes formed and weakest back mixing was found. Liquid velocities in riser from high to low were as follows: Fig. 4 b, a, c. In conclusion, the hydraulic mixing characteristics of the reactor were best and liquid velocity in riser was higher when H/D was 3 in three different situations.

There were two principle reasons about the above phenomenon[7]: (1) Gas lift function would be decreased when the energy consumption of internal circulation increased; (2) Massive gas did not outflow in time so as to increase the pressure in gas-collecting hood, which resulted in decreasing of pressure difference between the both sides of riser.The first IC reactor (1989) was built in DenBdsch of Netherlands, which volume and H/D was 970m^3 and 3 respectively[8]; an IC reactor built in Doosendaal of Netherlands was used to treat chicory wastewater, which volume and H/D was 1100m^3 and 2.8 respectively[9]; an IC reactor built in Shanghai of China was used to treat brewery wastewater,

which volume and H/D was 400m^3 and 4 respectively[10].

According to our simulation results, optimum value of H/D by calculating results was 3, which were very in accordance with above engineering practices.

Conclusions

In this paper process of gas-liquid two-phase flow in IC reactor (25L) was successfully simulated by fluent method. The change of Q_{IC} under different operation conditions (inflow and influent COD concentration) is investigated and correlation between Q_{IC} and biogas production was gained, which will provide much help for controlling operation of IC reactor. Meanwhile Q_{IC} under different D_r/D and H/D is investigated in this paper, which will provide technical means for optimal structure design of IC reactor (such as riser diameters, H/D).

Nomenclature

C_D drag coefficient, dimensionless $C_{1\varepsilon}, C_{2\varepsilon}$ constant, dimensionless
D   reactor diameter, m D_r riser diameter , m
F   interaction force between phases, N F_D drag force, N
f   drag coefficient, dimensionless $G_{k,m}$ turbulent kinetic energy, m^2/s^2
H   height of reactor, m K_{pk} momentum exchange coefficient, dimensionless
OLR   volume loading rates, kgCOD/(m^3·d) Q_{IC} inner cycle flow rate, m^3/h
R_e Reynolds number, dimensionless   ν   phase velocity, m/s
v_m velocity of mixture, m/s   ε   turbulence dissipation rate, m^2/s^3
μ   molecular dynamic viscosity, Pa·s ρ_m density of mixture, kg/m^3
ρ   density, kg/m^3 $\sigma_k, \sigma_\varepsilon$ turbulent Prandtl numbers, dimensionless
$\bar{\bar{\tau}}$ Reynolds-stress tensor, N/m^2 τ   particle relaxation time, s
φ   volume fraction, dimensionless
Subscripts
g   gas   k   k-th phase   L   liquid   p   p-th phase

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