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METHANOGENIC GRANULE DEVELOPMENT IN FULL SCALE INTERNAL CIRCULATION REACTORS

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ABSTRACT

Internal Circulation (IC) reactors can be operated at higher reactor volume loading rates than Upflow Anaerobic Sludge Blanket (UASB) reactors. This results in increased gas production rates and subsequently higher average shear rates in IC-reactors. Furthermore, the liquid upflow velocity is 8–20 times higher, still granules develop successfully in IC-reactors. To investigate the granule development in IC-reactors and elucidate the process limitations with respect to granule development and biomass retention, granule samples from three full scale IC-reactors are characterized. Characterization included size distribution, strength, settling velocity, density, ash content and methanogenic activity. Granules were compared with samples from UASB reactors treating similar types of wastewaters. A hydrodynamic model was developed to describe the liquid circulation in IC reactors. The average shear rate in IC reactors is approximately twice as high compared to UASB-reactors. The two stage design of the IC-reactor allows 3–6 times higher loading rate. The experimental results showed that IC-granules are larger than UASB-granules grown on similar wastewater, while the strength of IC-granules is lower as a result of the higher sludge loading rate. Although wash-out is slightly enhanced in IC-reactors, the conditions in the second stage are tranquil enough to ensure adequate biomass retention in IC-reactors. The development of characteristic IC-granules after seeding proceeds within a few months. Physical characteristics of granules are determined mainly by biological factors.

KEYWORDS

Anaerobic wastewater treatment; biofilm; biomass; granular sludge; granule characterization; Internal Circulation reactor; industrial wastewater; modelling; three-phase-separation, UASB-reactor.

INTRODUCTION

The last decade many full scale UASB-reactors have been constructed to treat industrial wastewaters (Lettinga *et al.*, 1980, Lettinga *et al.*, 1986). The limitations of UASB-reactors are related to the wash-out of biomass. For low-concentration wastewater the reactor volumetric loading rate (kgCOD/m^{3}d) is limited to 5–8 kgCOD/m^{3}d to avoid wash-out of suspended solids due to the liquid upflow velocity (Fang *et al.*, 1989, Vereijken *et al.*, 1986). At this loading rate the minimum hydraulic retention time is 4–5 h. For high-concentration wastewaters the reactor volume loading rate is usually restricted to 10–20 kgCOD/m^{3}d, to avoid wash-out of suspended solids due to increased turbulence at elevated gas rates (Rozzi *et al.*, 1988).

To overcome these limitations a two stage UASB-reactor called the Internal Circulation (IC) reactor was developed by Paques BV (Fig. 1). For concentrated wastewaters (5–9 kgCOD/m^3) reactor volume loading rates of 35–50 kgCOD/m^{3}d could be employed in IC-reactors (Hack *et al.*, 1988, Vellinga *et al.*, 1986). For low concentrated wastewaters (1.5–2.0 kgCOD/m^3) a reactor volumetric loading rate of 20–24 kgCOD/m^{3}d could be employed, at a hydraulic retention time of 2.1 h (this study).

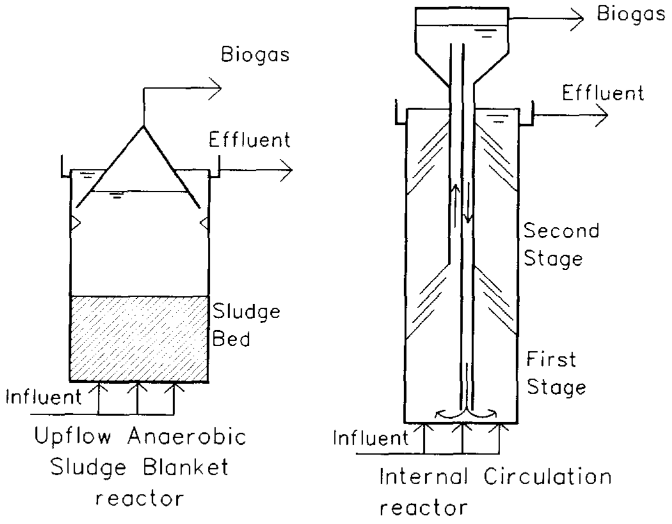

Fig. 1. Schematic presentation of UASB and IC reactor.

IC-reactors consist of two UASB compartments on top of each other. In the first (bottom) stage of the IC-reactor most biogas will be produced. The biogas will be trapped in the first section of gas-hoods and will rise through the riser section to a gas–liquid separator placed on top of the reactor including liquid to be recycled. The liquid flows back through the downcomer to the first stage. The biogas production thus drives an internal circulation flow, which results in excellent mixing in the bottom section and gives the reactor its name. In the second (top) stage biomass retention and/or polishing takes place. The gas loading of the second stage is limited, due to the early removal of biogas in the first stage. The high turbulence and adequate mixing characteristics makes the IC-reactor an attractive option for treatment of high strength wastewater (Rozzi *et al.*, 1988), or wastewaters which can cause problems with agglomeration of proteins (Sayed *et al.*, 1988) or long chain fatty acids (Rinzema *et al.*, 1990).

When compared to the UASB-reactor the IC-reactor can be operated at higher reactor volume loading rates at equal removal efficiencies. This results in an elevated gas production rate and a subsequent higher average shear rate in the first stage of the IC-reactor. Based on abrasion rates of methanogenic granules (Pereboom, 1994), it is not expected that this increased turbulence level directly results in a selection pressure for stronger or smaller granules. However, an increased fines formation rate could indirectly influence the size distribution of granules.

The biomass retention in the second stage of the IC-reactor is not hindered by excessive gas production, therefore, the hydraulic retention time in the reactor can be shortened to 2–2.5 h when low-concentration wastewaters are treated. The average liquid upflow velocity in the IC-reactor could be up to 20 times higher than in UASB-reactors, treating similar wastewaters. It is expected that the wash-out and retention of granules and more particularly fines is strongly influenced by these higher liquid upflow velocities. To elucidate the influence of higher production rates and changed retention factors of fines on the granule size distribution, granule samples of IC-reactors were studied.

TABLE 1. Process and Sludge Characteristics of Studied Reactors

reactor type	UASB	UASB	IC	IC	UASB	IC	
Used sample code	IND	BAV	ICP	ICF	AVI	CAB	
Wastewater type	paper	brewery	brewery	brewery	potato	potato	
Volume	2200	1400	50	6x162	2x1700	100	m^3
Height	5.5	6.4	22	20	5.5	15	m
HRT	4.5	6	2.3	2.1	30	4.0	h
Volume loading rate	5.7	6.8	20	24	10	48	kgCOD/m^{3}d
Sludge loading rate	0.1	0.2	0.7	0.96	0.35	1.3	gCOD/gVSSd
Biogas production	1.4	2	5.5	-	3	-	m^3/m^{3}d
Reactor temperature	25	23	24-28	31	-	-	°C
Influent COD	1.3	1.7	1.6	2.0	12	6.0-8.0	kgCOD/m^3
Influent SS	0.03-0.1	0.2-0.3	0.4-0.6	0.3-0.5	1.0-1.6	-	kg/m^3
Effluent COD	0.4	0.3	0.24	0.4	0.6	1.0	kgCOD/m^3
Effluent SS	0.08	0.2-0.8	-	0.4-0.5	0.3	1.1	kg/m^3
Efficiency COD	0.70	0.80	0.85	0.80	0.95	0.85	-
Dry matter (TSS)	80	73	60	52	50	55	kgTSS/m^3
Ash fraction	0.26	0.20	0.13	0.15	0.20	0.13	-
Fines fraction	0.02	0.09	0.14	0.09	0.04	0.04	-
Ash granules	0.26	0.19	0.12	0.15	0.20	0.14	-
Ash fines	0.34	0.41	0.17	0.15	0.35	0.06	-
Maximum diameter	3.43	3.42	3.14	3.22	3.38	3.57	mm
Average diameter	0.83	0.60	0.84	0.66	0.51	0.87	mm
Sauter mean	1.17	1.13	1.59	1.31	1.07	1.78	mm
Number of granules	1.24	1.78	0.46	1.00	2.05	0.49	x10^9 m^{-3}
Density	1065	1054	1057	1041	1039	1043	kg/m^3
Wet biomass	180	170	157	152	115	139	kgTSS/m^3
Relative strength	1.00	0.83	0.32	0.51	0.71	0.53	-
Potential activity	0.60	1.10	1.40	1.90	1.08	1.83	gCOD/gVSSd
Potential activity 2nd stage				1.75		1.60	gCOD/gVSSd
Effectiveness	0.17	0.50	0.51	0.33	0.71	-	

Samples from reactors treating low strength brewery wastewaters (ICP, ICF and BAV) and high strength potato processing wastewaters (AVI and CAB) were chosen to study the influence of sludge and volume loading. The studied IC-reactors were (originally) seeded with UASB-granules from a reactor treating papermill wastewater (IND). The evolution of granules was studied by regular sampling after seeding in one of the studied IC-reactors (ICP).

A hydrodynamic model is presented to estimate the liquid recirculation over the riser and downcomer of the IC-reactor. The average shear rate in methanogenic reactors is based upon superficial liquid and gas velocities which determine the energy dissipation rate. Size distributions of IC- and UASB-granules were measured along with individual settling velocities, density measurements of total and size classified samples, while effluent samples are characterized as well in order to estimate granule and fines retention factors.

Since it is difficult to simulate UASB hydrodynamics on lab scale, data from full scale reactors were used to investigate granule evolution and development. Comparison of granule characteristics from full scale reactor data is not an easy matter. Wastewater volume, concentration and composition may vary considerably in time, so that granule grab samples of a specific moment have a limited value. Most of the reactors studied have been sampled multiple times.

MATERIALS AND METHODS

Sludge sampling. The reactor sludge samples were taken from sample ports at several heights. The sample ports located at 1.0–1.5 m from the bottom of UASB-reactors and at 4–5 m from the bottom of the IC-reactor are considered to be representative for the reactor content. Since IC-reactors can be up to 22 m high, precautions had to be taken to prevent the granules from damage by fast pressure drops. Therefore, sampling was performed using a vessel filled with CO_2 at a pressure of 2.5 atm (1 atm. ≈ 0.1 MPa. The IC reactors studied were treating brewery wastewater (ICP on pilot scale and ICF on full scale), and potato processing wastewater (CAB). Thus granules developed on diluted (brewery) and concentrated (potato) wastewater were studied. The granules from the IC reactors were compared with granules developed in UASB reactors treating similar wastewaters (BAV, AVI) and compared to the seeding material (IND). The reactors were operated continuously. The relevant reactor parameters are presented in Table 1.

Physical granule characterisation. The sludge samples, which may contain up to 4000 particles per ml, were diluted 20–30 times with tap water in a gaslift mixer, from which smaller samples could be taken through a large sampling port (∅ 8 mm). The size and number of granules were determined by use of an image analyzing system (Pereboom *et al.*, 1988b). For each granule the diameter was estimated (Dp = 0.5[longest cord + width]). Based on individual diameters the average mean diameter (Da) and the Sauter diameter (D32) of the granule samples were calculated. Granules too small (< 150 μm) to be measured were decanted or sieved from the sample and designated as fines. The strength was based on shear experiments in a 300 ml standard geometry vessel at increasing stirrer speeds (Pereboom *et al.*, 1990). The strength is presented as the abrasion rate coefficient (ARC) relative to the strongest sample studied ($\text{strength}=ARC_X/ARC_{IND}$).

The settling velocity of the granules was calculated from the experimentally determined settling time in a 1.6 m water column, while the individual size was determined from photographic recordings at this depth (Pereboom *et al.*, 1988b). The density of sieved and paper tissue dried granules was measured at room temperature with a pycnometer which was degassed before closing (Hulshoff Pol *et al.*, 1986). By measuring the VSS after pycnometer measurements the biomass concentration of the granules or wet biomass could be calculated. Total suspended solids and volatile suspended solids were measured according to Standard Methods.

Size classification was achieved by wet sieving (Pereboom *et al.*, 1988a) in perspex cylinders (∅ 65 mm x 100 mm) equipped with a sieve plate. After filling the sieve column with mineral medium and placing the sample on top, it was flushed with nitrogen gas. During gentle intermittent swirling the granules settle through the sieve plates according to their size.

Sludge activity. The potential acetoclastic sludge activity was measured in unstirred 500 ml serum flasks filled with approximately 0.15 gTSS of granules and nutrients at 30°C (Pereboom *et al.*, 1988a). Acetate was added to the required concentration or the standard 40 mol/m^3. To ensure a more or less constant substrate level, additional substrate was supplied when 10 % of the original substrate was converted, as measured by the methane production in Mariotti flasks containing 3 M NaOH. After the tests the SS and VSS were measured. The effectiveness factor is defined as the actual sludge activity, based on reactor performance, divided by the potential activity measured at 40 mol/m^3 HAc in the activity test.

RESULTS AND DISCUSSION

Liquid recirculation

One of the most characteristic features of the IC-reactor is the recirculation of liquid over the riser and downcomer. By use of hydrodynamic models for gas lift reactors the internal recirculation flow can be estimated. The gas hold-up in the riser (ε_{gr}) can be estimated by an empirical relation between superficial gas (u_{gr}) and liquid (u_{lr}) velocities in the riser as measured by Hills (1976):

$$\varepsilon_{gr} = \frac{u_{gr}}{0.24 + 1.35\left(u_{gr} + u_{lr}\right)^{0.93}} \qquad (1)$$

This relation was studied in a gaslift reactor with a riser diameter of 0.15 m and a height of 10.5 m. The relation was verified for superficial gas velocities of 0.07–3.5 m/s and superficial liquid velocities of 0.3–2.7 m/s, well within the values of the riser section of the IC-reactor.

Based on the gas hold-up in the riser (ε_{gr}) and system (design) parameters (Pereboom, 1989) the superficial liquid velocity in the riser (u_{lr}) can be estimated by a modified relation for gaslift loop reactors (Chisti *et al.*, 1988), which is based on the systems energy balance:

$$u_{lr} = \left(\frac{2\ g\ \left[h_D \left(\varepsilon_{gr} - \varepsilon_{gd} \right) - \Delta h \right]}{\left(\frac{K_T}{\left(1 - \varepsilon_{gr}\right)^2} \right) + K_B \left(\frac{A_r}{A_d} \right)^2 \left(\frac{1}{\left(1 - \varepsilon_{gd}\right)^2} \right)} \right)^{0.5} \qquad (2)$$

In this equation several system characteristics are used; gas rising height (h_D), difference in liquid height between riser and downcomer (Δh), resistance coefficients of top and bottom section ($K_{B/T}$), cross section area of riser and downcomer ($A_{r/d}$) (Pereboom, 1989).

Similar theoretical relations were described and verified for superficial liquid velocities of 0.05–1.0 m/s (Verlaan *et al.*, 1986). The driving force, for liquid circulation, is the pressure difference between riser and downcomer as a result of the difference in gas hold-ups (ε_{gr}-ε_{gd}). The liquid height in riser and downcomer of the IC-reactor was not the same, therefore a correction term (Δh) was introduced, which was approximately 0.4 m for the IC-reactors investigated. The gas hold-up in the downcomer due to entrainment or production of gas was arbitrarily, estimated to be 5 % of the hold-up in the riser. The resistance coefficient of the top section (K_T) was zero, since the riser of the IC-reactor ends openly in the two-phase-separator at the top of the reactor. Based on literature results (Chisti *et al.*, 1988, Verlaan *et al.*, 1986) the resistance coefficient of the bottom section (K_B) was estimated to be 8.0. Based on liquid recirculation flow measurements from another pilot scale IC-reactor (Vellinga *et al.*, 1986), a resistance coefficient (K_B) of 32 could be calculated. The downcomer in that particular IC-reactor was an external one, with several extra bends, which resulted in a higher resistance coefficient (K_B). By use of equation (1) and (2) the superficial liquid velocity in the riser could iteratively be calculated, while the recirculation flow could be calculated from the superficial liquid velocity (Table 2). For the calculations of the liquid recirculation flow, both values of K_B (8 and 32) were used.

Average shear rates. The estimation of the average shear rates (γ) in methanogenic reactors was based on the energy dissipation rate (ε). The energy dissipation rate in three phase upflow systems is equivalent to the superficial liquid (u_l) and gas (u_g) velocities in the reactor and average system density, as can be related to holdup of solids (ε_s) and gas (ε_g). Thus the energy dissipation rate for gassed fluidized bed systems has been described by Lee and Buckley (1981):

$$\varepsilon = \frac{\left[\rho_s\, \varepsilon_s \left(u_l + u_g\right) - \rho_l\, u_l \left(1 - \varepsilon_l\right) + \rho_l\, u_g\, \varepsilon_l \right]\ g}{\varepsilon_l\ \rho_l} \qquad (3)$$

TABLE 2. Estimated Average Shear Rates in Studied Reactors

Reactor type	code	K_B	Recirculation flow [m^3/h]	u_l [mm/s]	u_g [mm/s]	ϵ x10^{-3}[m^2/s^3]	$\dot{\gamma}$ [s^{-1}]
UASB	IND			0.3	0.07	1.4	14
	BAV			0.3	0.14	3.7	22
	AVI			0.08	0.19	3.2	21
IC (first-stage)	ICP		0	2.4	0.56	9.6	36
		32	60	7.6	0.56	10.9	38
		8	70	8.5	0.56	11.0	38
	ICF		0	2.7	0.56	9.0	35
		32	60	4.7	0.56	9.4	35
		8	95	5.9	0.56	9.7	36
	CAB		0	1.4	2.0	36	69
		32	80	5.8	2.0	37	70
		8	130	8.6	2.0	38	71

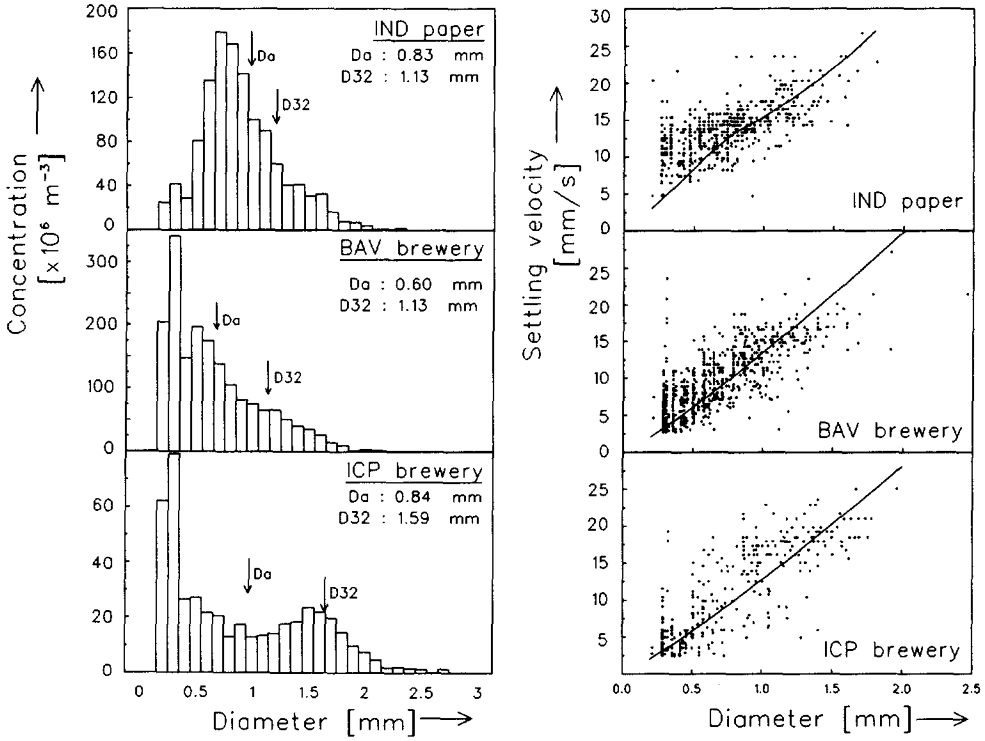

Fig. 2a–f Size distribution (left; a,c,e) and individual granule settling velocity (right: b,d,f) of UASB and IC samples, grown on paper and brewery wastewater.

The energy dissipation rate as described by Lee and Buckley (1981) is the sum of the energy input by evolved or introduced gas and by the liquid flow through the fluidized bed. The sludge bed in UASB-reactors is expanded, but can not be described as completely fluidized, which limits the use of the above relation. So far, a more precise theoretical prediction of the energy dissipation rate can not be made, while experimentally it can not be measured in this system. In UASB-reactors the largest part of the energy dissipation rate is related to the gas evolvement.

The time average shear rate ($\dot{\gamma}$) is related to the energy dissipation according to Taylor (1935):

$$\dot{\gamma} = \left(\frac{2}{15}\right)^{\frac{1}{2}} \left(\frac{\epsilon}{\eta}\right)^{\frac{1}{2}} \tag{4}$$

This equation is only valid if an isotropic and homogeneous turbulent flow field exists. This condition is satisfied if mixing is highly turbulent.

The superficial liquid velocity in the first stage of the IC-reactor was related to the influent flow plus the internal recirculation flow over riser/downcomer. The superficial gas velocity was corrected for the actual pressure in the first stage. The solid holdup was based on TSS and wet biomass measurements.

The estimated average shear rates in the IC-reactors were higher than in the UASB-reactors (Table 2). This was caused by the higher superficial gas velocity in the first stage, which is a result of higher H/D-ratio and the higher volumetric loading rate of the IC-reactor. The internal recirculation flow had little effect on the shear rate, but enhances significantly the mixing or axial dispersion in the first stage.

Sludge characteristics

Representative reactor and granule characteristics are presented in Table 1. The IC-reactors showed higher volumetric and sludge loading rates and a shorter HRT compared to the UASB-reactors. The effectiveness, expressed as the reactor sludge loading divided by the measured sludge activity at 40 mol/m^3 HAc, is more than two times higher in IC-reactors. This indicates that the potential sludge activity is more efficiently used in these reactors.

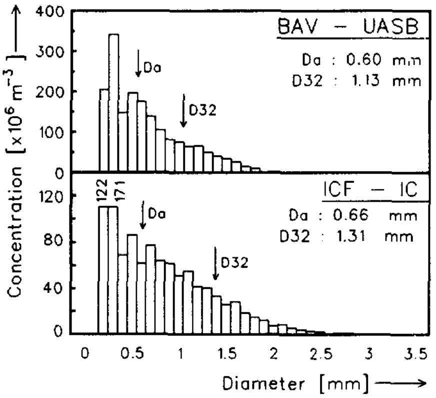

Fig.3.a Size distribution of granules developed in UASB and IC reactors on brewery wastewater.

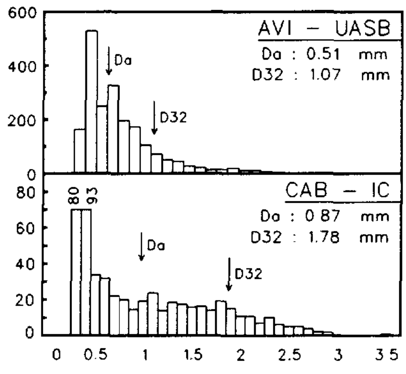

Fig.3.b Size distribution of granules developed in UASB and IC reactors on potato wastewater.

The relative strength of IC-granules is lower than UASB granules (Table 1). The higher sludge loading rate results in a lower strength of the granules, which is in accordance with observations in UASB-reactors (Pereboom 1994).

The solids concentration (TSS) in IC reactors is lower than in UASB-reactors. The higher superficial liquid and gas velocities in the first stage result in expansion of the sludge bed (Han *et al.*, 1990). However, the reactor average solid concentration was higher in IC-reactors, since a larger part of the reactor can be occupied by the sludge bed.

Size distribution. Comparison of the size distributions of granules from UASB and IC reactors, show larger granule sizes (Sauter mean) and wider distributions in IC reactors (Fig.2 and 3.a-b). This wider size distribution can be explained by the easy wash-out from IC-reactors of precursors (fines) for new granules. As more fines are removed from the system by the effluent, less sluicing is required and the granules will stay longer in the system and will thus grow larger (Pereboom 1994). The higher selection pressure results in wider size distributions. Observations on granule size distributions in IC-reactors are in accordance with experiments by Guiot *et al.* (1988), in which the granules size in UASB reactors increased at increased hydraulic loading rates.

Settling velocity. The settling velocities (Fig. 2b,d,f) are always higher than the liquid upflow velocity in the UASB and IC-reactors. The settling velocities of small (<0.5 mm) IC-aggregates are only slightly higher (ICF: u_l=2.6 [mm/s]) than the liquid upflow velocity. The experimental settling velocities are in qualitative agreement with the calculated settling velocities at intermediate Reynolds numbers ($Re = 5-100$), as indicated by the lines in the graphs (Fig. 2b,d,f). The low gas loading in the second stage created tranquil settling conditions resulting in good retention of small particles in the second stage.

Visual observation. Paper (IND) and potato (AVI, CAB) granules are very regular and have a smooth black surface. Granules grown on brewery wastewater (BAV, ICP and ICF) are more irregular, somewhat spherical, have a lighter colour and white spots on the surface. These white spots probably contain acidifying bacteria related to the sugar-containing wastewater. The first weeks after seeding of the ICP- and ICF-reactors original and new developed granules were observed simultaneously.

Granule development after seeding. The granule development in the ICP reactor was studied, after seeding with IND-granules by regular sludge sampling. The size distribution quickly develops to values representative for the IC reactor (Fig. 4). The number of small granules increases, but the biomass concentration in the reactor did not considerably vary in time. After a few weeks the wider characteristic IC size distribution developed. Due to the high growth rate in the IC-reactor, granule development is completed within 2 months after seeding.

Size classified samples. Size classified samples were studied to investigate the granule characteristics in different size classes (Table 3). Granules larger than 0.8 mm represent approximately 80 % of the total biomass in the IND-reactor. This is in agreement with biomass size distribution (Hulshoff Pol *et al.*, 1986). Smaller IND-granules show a higher ash fraction and a higher density than larger granules. Sofar, it is not clear why the ash fraction of smaller granules is higher than that of larger granules. Such relation was not found for fast growing IC-granules. A positive relationship between ash fraction and density of methanogenic granules has been shown before (Hulshoff Pol *et al.* 1986, Pereboom 1994). Sludge characteristics in IC-granules do not vary over the different size classes, indicating high growth and fast development.

Small IND-granules show a lower activity at 40 mol/m^3 HAc. Also small IC-granules show a slightly lower activity at 40 mol/m^3 HAc. The activity measurements at 4 mol/m^3 HAc (approximately reactor concentration) show that for ICP-sludge the activity is higher for smaller granules. This suggests that at 4 mol/m^3 mass transport limitations inside large granules occurs in the unstirred activity test.

The potential activity of IC-sludge measured at reactor concentrations of 4 mol/m^3 HAc in the unstirred activity test, are much lower than the actual activity found in the reactor. This can be explained by internal and/or external mass transfer limitations at low substrate concentrations during the unstirred activity test, while these mass transfer limitations do not occur in the IC-reactor due to sufficient mixing. Higher sludge activities were reported before at elevated stirrer speeds in stirred UASB-reactors (Chang *et al.*, 1986).

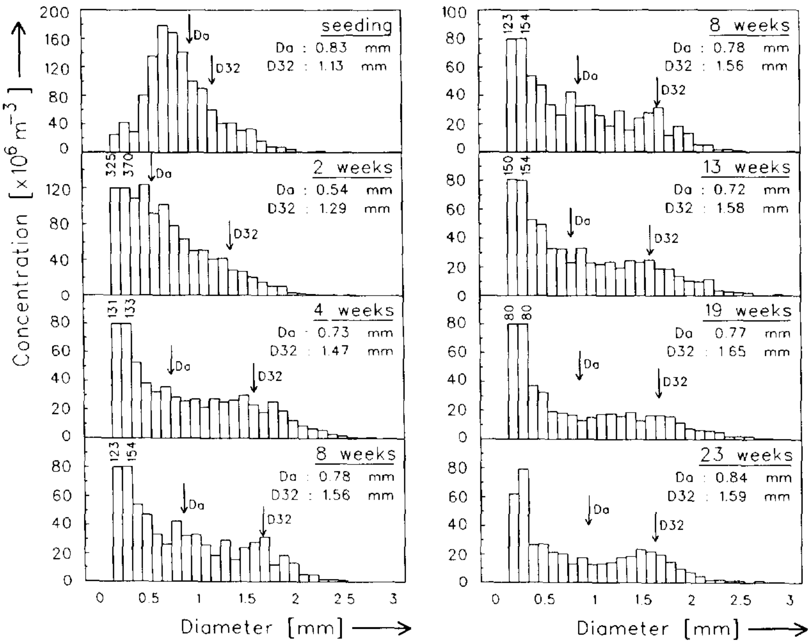

Fig. 4. Granule development in ICP, from 2–23 weeks after seeding with IND granules.

TABLE 3. Characteristics of Size Classified Granule Samples

Sample code		size classes					total	
		A	B	C	D	E		
	diameter sieve	2.18	1.68	1.15	0.91			
IND-1	Da	2.56	1.57	1.14	0.83	0.60	0.83	mm
	D_{32}	2.87	1.69	1.26	0.91	0.69	1.17	mm
	fraction of TSS	0.08	0.15	0.42	0.20	1.0		-
	density	1055	1058	1058	1078	1084	1062	kg/m^3
	ash fraction	0.20	0.24	0.24	0.30	0.42	0.26	-
	activity *	0.61	0.62	0.56	0.49	0.11	0.60	gCOD/gVSSd
IND-2	density	1063	1059	1070	1074	1063	1065	kg/m^3
	ash fraction	0.19	0.21	0.25	0.31	0.32	0.25	-
	activity *	0.73	0.78	0.82	0.65	0.17	0.65	gCOD/gVSSd
	wet biomass	167	175	196	208	172	180	kgTSS/m^3
ICP	density	1042	1041	1041	1057	1047	1057	kg/m^3
	ash fraction		0.11	0.11	0.09	0.14	0.12	-
	activity *		1.29	1.55	1.50	1.15	1.25	gCOD/gVSSd
	activity #		0.30	0.32	0.31	0.39	0.17	
	wet biomass	150	152	158	167	165	157	kgTSS/m^3
CAB	fraction of TSS	0.34	0.31	0.26	0.04	0.05	1.00	-
	ash fraction	0.22	0.19	0.19	0.19	0.25		-
	activity *	2.34	2.27	2.34	2.00	1.92	1.83	gCOD/gVSSd
	fines fraction $	0.07	0.12	0.11	0.09	0.25		-

* measured at 40 mol/m^3 HAc, # measured at 4 mol/m^3 HAc,
$ as measured after activity measurement.

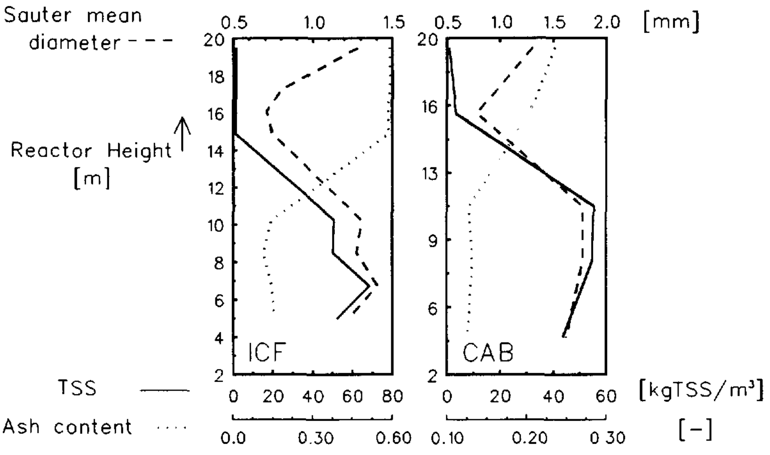

Fig. 5. Granule size, biomass concentration and ash-content at different heights in full scale IC-reactors treating brewery (ICF) and potato (CAB) wastewater.

TABLE 4. Reactor and Effluent Characteristics of Studied Reactors

Sample code	IND		BAV		ICF		AVI		CAB		
Sample point	reac.	eff.	reac.	eff.	reac.	eff.	reac.	eff.	reac.	eff.	
Dry matter (TSS) kgTSS/m³	100	0.082	50	0.83	51	0.5	50	0.31	55	1.1	
Ash fraction	0.14	0.14	0.16	0.43	0.15	0.60	0.20	0.15	0.13	0.24	-
Fines fraction	0.004	0.85	0.043	0.80	0.09	0.85	0.036	0.50	0.037	0.93	-
Biomass retention	1220		60		100		163		50		-
Granule retention	7810		290		610		310		690		-
Fines retention	5.3		3.2		11		11.7		2		-
Biomass removal:											
by sluicing			0.005		0.0		0.013		0.007		d^{-1}
by effluent			0.07		0.16		0.01		0.17		d^{-1}
Maximum dia.	2.63	3.79	2.67	3.06	3.22	2.1	3.38	3.64	3.57	3.10	mm
Average dia.	0.94	0.30	0.86	0.31	0.66	0.3	0.51	0.57	0.87	0.3	mm
Sauter mean	1.17	0.80	1.33	0.83	1.31	1.32	1.07	0.99	1.78	1.45	mm
Numb.of granules	110	0.21	79	0.25	100	-	205	0.38	49	-	$x10^7$ m^{-3}

Granule characteristics over IC-reactor height. From the size distributions (Fig. 6) and the granule characteristics (Fig. 5) at different reactor heights, it can be concluded that the sludge bed in the first stage of the IC-reactor is well mixed. The ash content of solids present above the sludge bed and in the effluent are much higher than in the sludge bed. It can be concluded that inorganic materials are efficiently removed from the highly turbulent IC-reactor. The sludge activities of the second stage samples (Table 1) were only slightly lower than in the first stage, which indicates that sludge was readily exchanged between the two stages.

Wash-out of biomass. The higher shear rate and lower granule strength are expected to result in more granule attrition and subsequently higher concentrations of fines. Due to the higher superficial liquid velocity these fines are washed-out and the reactor concentrations are similar to UASB reactors. Comparison of the net biomass removal by sluicing and by wash-out (Table 3), shows that indeed more suspended (or even all: ICF) biomass is removed from IC reactors by the effluent. Due to the lower sluicing rate, granules could remain longer in the reactor and grow larger.

CONCLUSIONS

The two stage design of the IC-reactor allows 3–6 times higher reactor volumetric loading rates compared to UASB-reactors, treating similar wastewaters. The biomass effectiveness is higher in IC-reactors than in UASB-reactors. The IC-design prevents high turbulence in the final three-phase-separator and thus prevents wash-out of granules.

The average shear rate in IC-reactors is approximately twice as high as in UASB-reactors. This is caused by the higher gas production and the taller reactor design of the IC-reactor. The first stage of the IC-reactor is well mixed due to high superficial gas velocities and the internal recirculation flow. The latter was estimated to be between 0.5 and 5.0 times the influent flow.

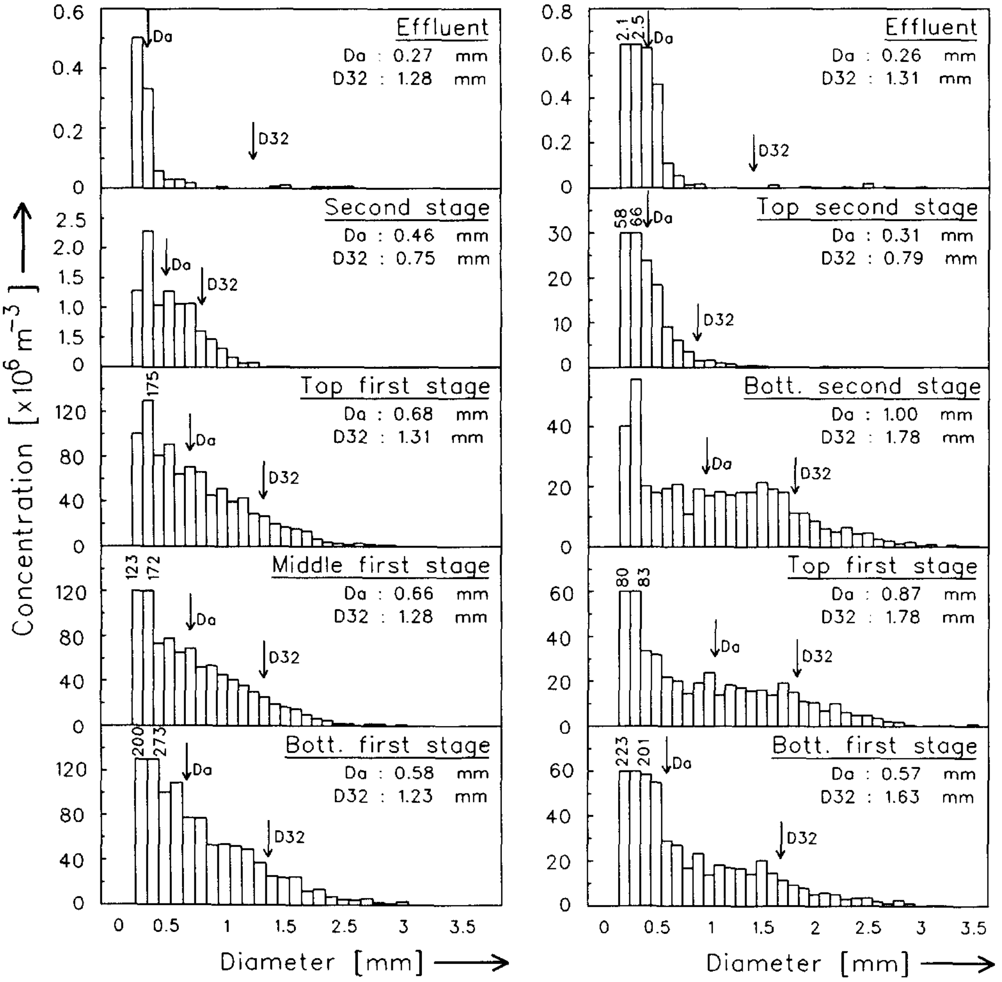

Fig. 6. Granule size distribution at different heights in IC reactors and effluent, treating brewery (left, ICP) and potato (right, CAB) wastewater.

The short HRT combined with the high H/D-ratio of the IC-reactor resulted in a higher solids (fines) wash-out in the IC-reactors when compared to the UASB-reactors. The larger granule size in IC-reactors is the result of increased solids wash-out as fines, resulting in lower sluicing rate. The higher sludge loading rates and subsequent higher growth rates in the IC-reactors resulted in the development of granules with a lower strength. The development of characteristic IC-granules from seeded UASB-granules proceeds within a few months. Physical characteristics of granules are influenced to a larger extent by biological rather than hydrodynamical factors.

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