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Water Practice & Technology Vol 14 No 4
doi: 10.2166/wpt.2019.066

Biopaq®ICX: The next generation high rate anaerobic reactor proves itself at full scale

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Abstract

The ICX (Internal Circulation eXperience) is the next generation high rate anaerobic reactor. The unique design with a two-stage phase separation device enables excellent biomass retention. The novel biomass retention device allows for high volumetric loading rates to be applied compared to IC (internal circulation) and UASB (Upflow Anaerobic Sludge Bed) reactors. Since the first demonstration test in 2013, more than 70 full scale ICX reactors have been built, ranging in size from 85 to 5,000 m^3. This paper presents the results of the first ICX demonstration reactor (85 m^3) and from a full scale ICX reference (350 m^3). These results confirm that very high volumetric loading rates can be achieved with the ICX, whilst maintaining a stable and high COD removal efficiency. Biomass growth is clearly demonstrated in both the demonstration reactor and in the full scale reference, proving that efficient biomass retention is achieved in the ICX.

Key words: efficient biomass retention, high volumetric loading rate, next generation high rate anaerobic reactor

INTRODUCTION

The first high rate anaerobic UASB (Upflow Anaerobic Sludge Blanket) reactor in the paper industry was installed by Paques in The Netherlands in 1983. Instead of using energy to convert COD (mainly for aeration), methane is produced in the anaerobic process, resulting in a positive energy balance. Following the UASB reactor, Paques introduced the IC (Internal Circulation) reactor, which has been the leading technology for the past decades (Vellinga *et al.* 1986; van Lier *et al.* 2015).

Most recently, a third generation of high rate anaerobic bioreactors has been developed: the ICX reactor (IC eXperience). The unique design of the two-stage phase separation in this reactor results in outstanding performance and excellent biomass retention at higher volumetric loading rates. Figure 1 illustrates the working principle of the ICX reactor. Compared to UASB and IC reactors, the ICX reactor does not use three-phase separators. Instead, the separation of biogas and granular biomass takes place separately. The top separator in the ICX (see Figure 1) removes the biogas from the reactor contents. The bottom separator separates the anaerobic granular biomass from the effluent. A clear advantage of separation of the biomass in the bottom of the reactor is that the higher hydrostatic pressure reduces the buoyancy of granules that still contain some residual biogas. Granules that tend to float when separated from the water in the top of the reactor (near atmospheric pressure) will not float in the bottom separator of the ICX. This results in a higher biomass retention efficiency.

The rise of this third generation high rate anaerobic reactor is also reflected in the applicable volumetric loading (VLR), which is 10–15 kg COD/m^3/d for the UASB, 20–30 for the IC and 20–35 for the ICX. A higher volumetric loading rate compared to the IC is possible due to a larger fraction of the ICX being filled with active granular biomass. In IC reactors, the second compartment

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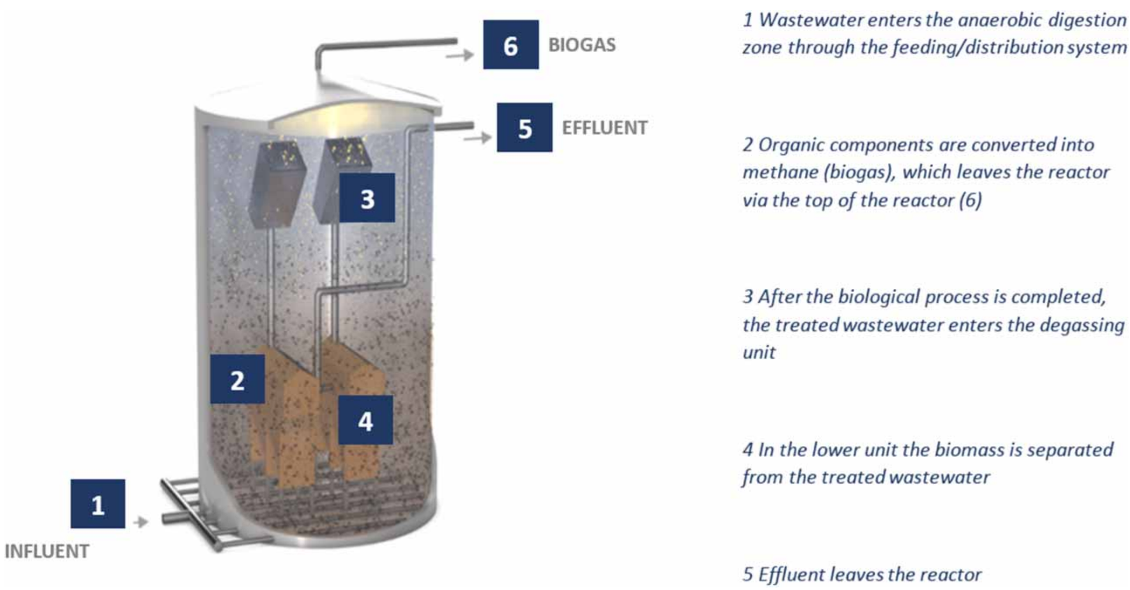

Figure 1 | Working principle of the Biopaq®ICX reactor.

is generally considered as a polishing step and contains little or no biomass, the ICX does not need this second compartment.

The performance of the ICX reactor was first tested in 2013 in an 85 m^3 demonstration reactor treating wastewater in the paper industry. In 2014 the first full scale ICX reactor was built; since then more than 70 full scale ICX reactors have been installed worldwide, ranging in size from 85 m^3 to 5,000 m^3. This paper presents the results of the first ICX demonstration reactor and of a full scale reference treating effluent from the paper industry.

MATERIAL AND METHODS

Liquid volumes of the ICX demonstration reactor and the full scale reference were 85 m^3 (12 m height and 3 m diameter) and 350 m^3 (16.9 m height and 5.1 m diameter), respectively. Influent composition and applied flow rates for both demonstration and full scale reference are given in Table 1.

Table 1 | Influent flow rate, reactor volume, volumetric loading rate and average influent composition for the demonstration ICX and the full scale ICX

Parameter	Unit	Demonstration ICX	Full scale ICX
Flow rate	m^3/h	20–90	15–60
Reactor volume	m^3	85	350
Volumetric loading rate	kg $COD/m^3/d$	18–50	8–28
Total COD	mg O_2/L	3,100	7,000
BOD	mg O_2/L	1,800	Not available

Both reactors treated effluent from the paper industry.

The amount of granular biomass in the ICX reactor was determined by taking Imhoff samples at different heights. The settled amount of granular biomass (in mL granules per L of sample) is then multiplied with the part of the total reactor volume that is represented by that sample height. The total amount of granules is the sum of these amounts for the different sample heights.

The specific methanogenic activity (SMA) of the anaerobic granules with acetate as a substrate was measured according to Soto *et al.* (1993) using the OxiTop© system to follow gas production rate.

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RESULTS AND CONCLUSIONS

ICX demonstration reactor

The results from the demonstration reactor (Figure 2(a)) proved that very high volumetric loading rates of over 50 kg COD/m^3/d can be achieved with the ICX reactor, as can be seen from Figure 3 and summarised in Table 2.

At the very high VLRs of 37–50 kg COD/m^3/d, similar total COD removal efficiencies of 72–74% were achieved (see Table 2). After significantly reducing the VLR to only 18 kg COD/m^3/d a clearly higher COD removal efficiency of 81% could be achieved.

The growth of anaerobic granular biomass was closely followed in period D (days 292–347). In this period of 55 days, a total of 63 m^3 of granular anaerobic biomass was grown (see Figure 4). In this

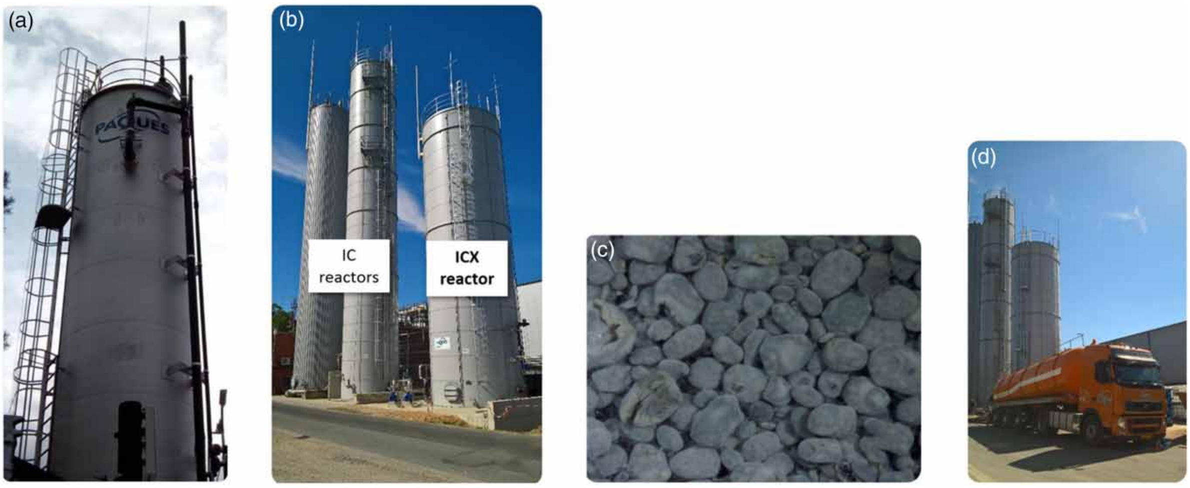

Figure 2 | Photos of the ICX demonstration reactor (a) full scale ICX installation (b), anaerobic granules cultivated in the full scale ICX reactor (c) and truck harvesting excess anaerobic granular biomass (d).

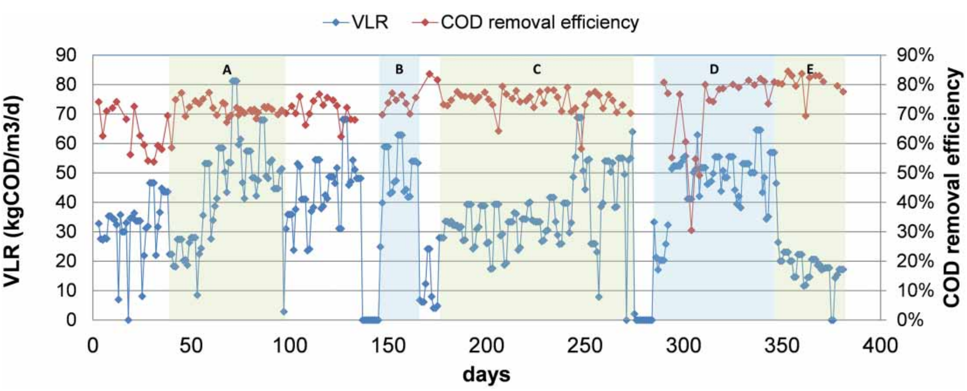

Figure 3 | Volumetric loading rate and COD removal efficiencies in the ICX demonstration reactor. The periods A-E correspond to those in Table 2.

Table 2 | Volumetric loading rates (VLR), total COD (tCOD) removal efficiencies and the effluent acetate concentration during 5 consecutive test periods (A-E) with the ICX demonstration reactor treating effluent from the paper industry

		A	B	C	D	E
Test days	#	53	19	98	61	34
VLR	kgCOD/m^3/d	45	50	37	47	18
tCOD removal	%	72	74	74	72	81
Effluent acetate	mg/L	61	59	64	65	8.4

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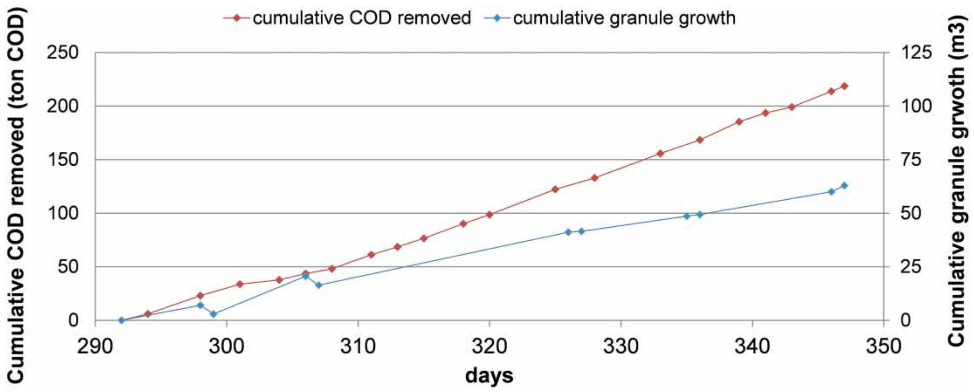

Figure 4 | Cumulative COD removed and granular biomass growth in the ICX demonstration reactor in period D.

same period, a total of 219 tons COD was removed. Using a biomass concentration of 64 g VSS/L granules, a biomass yield of 18 kg VSS per ton COD removed is calculated. When comparing this to reported growth yields of 15–39 g VSS/ton COD on water containing difference mixes of sucrose and VFAs (Hulshoff Pol 1989), it suggests that most of the anaerobic growth was retained as granular biomass. The higher and lower yields reported in literature may arise from differences in pre-acidification degree of the incoming waste water and the applied sludge retention time. The degree of acidification was not determined for the influent of the demonstration reactor.

The tests with the demonstration reactor served to determine the hydraulic and biological limits of the system under controlled conditions. By performing these demonstration tests at a fairly large scale (85 m^3 reactor), further upscale to larger full scale reactors could quickly be made. This has resulted in the commissioning of ICX reactors of up to 5,000 m^3 volume.

In the demonstration reactor, only part of the total paper industry effluent was treated, allowing it to operate at a constant influent flow rate and, therefore, a reasonably stable COD loading rate. Under these conditions a very high (50 kg COD/m^3/d) loading rate could be achieved without a loss in removal efficiency. In reality, fluctuations in flow- and loading rates exist and the average loading rate will be somewhat lower. This is shown in the results of the full scale ICX reference.

Full scale ICX reactor

The full scale ICX reactor was installed next to two existing internal circulation (IC) reactors (Figure 2(b)); the influent flow is divided between the three reactors. Figure 2(c) shows the morphologic characteristics of the granules from the ICX reactor.

Results presented in Figure 5 confirm a stable performance of the ICX reactor with a high COD removal efficiency (84.8% on average), established under volumetric loading rates of up to 28 kg COD/m^3/d. In this period, the ICX reactor treated all its incoming waste water, fluctuations in COD load were the result of the fluctuations in waste water supply.

In the presented period of 244 days, the ICX reactor consistently grew and retained granular biomass. Approximately 207 m^3 of excess biomass could be removed from the reactor, while maintaining its high COD removal efficiency, as shown in Figure 6. Combined with the converted COD load in this period, a specific growth yield of 12 kg VSS/ton COD is calculated. This yield is comparable to the yield found in the demonstration ICX reactor. This proves that excellent biomass retention is achieved with the 2-stage biomass retention device of the ICX, also under conditions of fluctuating flow rates that may occur in full scale applications.

The measured specific methanogenic activity (SMA) of the harvested granules was 1.1 g COD/g VSS/d. This is higher than the SMA values of 0.19–0.62 g COD/g VSS/d reported by Hulshoff Pol

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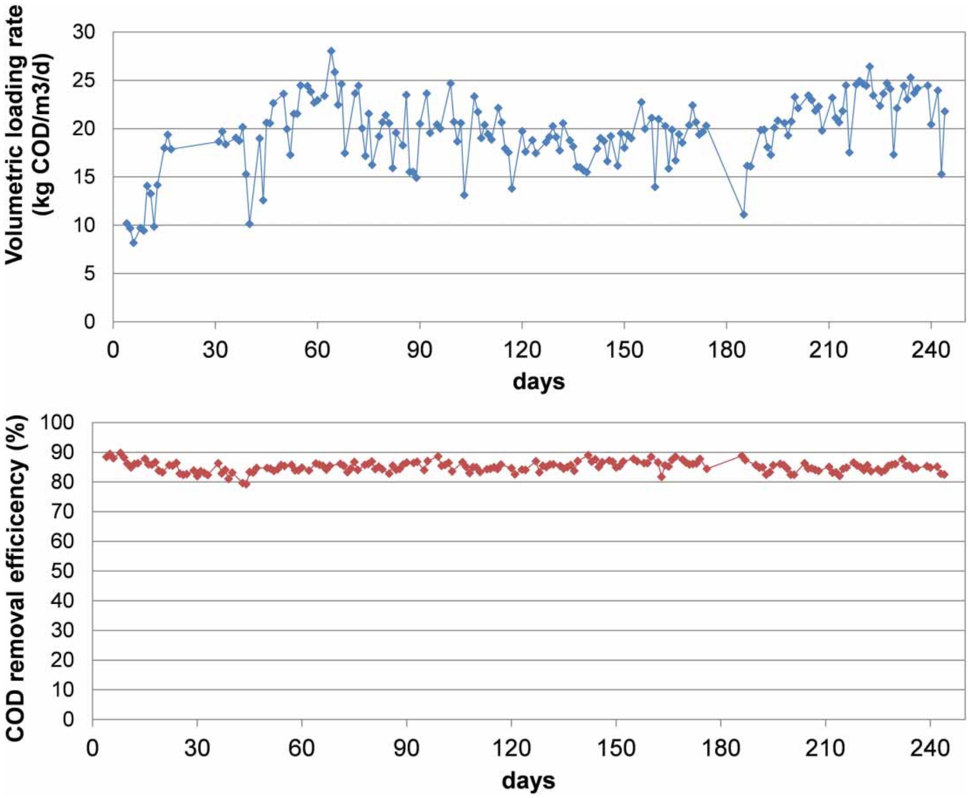

Figure 5 | Volumetric loading rate (top) and COD removal efficiency (bottom) in the full scale ICX reactor.

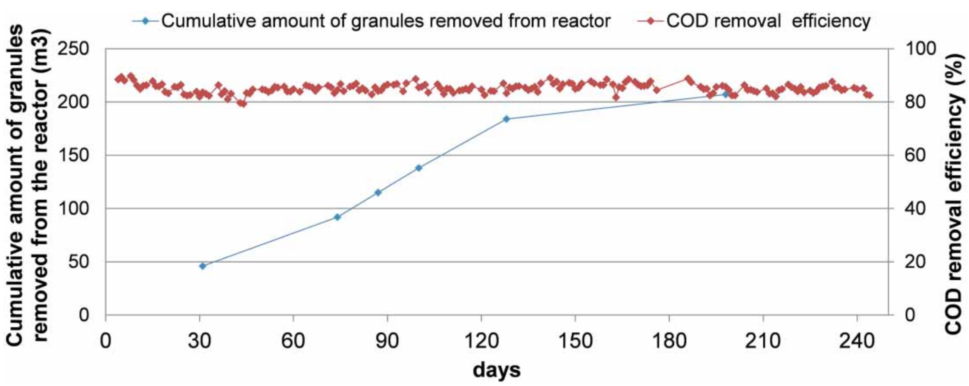

Figure 6 | Cumulative amount of granular biomass removed from the full scale ICX reactor and the COD removal efficiency.

(1989) for anaerobic granules from full scale installations treating paper mill effluents. The high SMA of the granular biomass in the ICX, in combination with excellent retention of this biomass, makes it possible to apply high VLRs and maintain a high COD removal efficiency.

CONCLUSIONS

The Biopaq®ICX is the next generation high rate anaerobic reactor that has proven itself at full scale.

Results from the first demonstration reactor and from the selected full scale reference showed:

- very high volumetric loading rates of more than 50 kg COD/m^3/d can be achieved
- high and stable COD removal efficiency under fluctuating loads

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- efficient biomass retention is achieved under fluctuating loading rates
- clear granular biomass growth in the reactor.

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