Chapter 3

Literature Review

3.1 The Brewing Process and the Sources of Pollution

3.1.1 The Brewing Process

The flow diagram of a typical brewery operation is shown in Fig. 3.1. The making of beer is basically conversion of starch to sugars so that yeasts can ferment the sugars to form alcohol and carbon dioxide. To begin with, malts are crushed or mashed in warm water and soaked. They are later slightly cooked in brewkettle at a stabilised temperature of about 65°C (when the breakdown of complex carbohydrates to sugars is rapidly completed) and then the temperature is raised to about 75°C, at which the enzymes are inactivated and the reactions are brought to an end. The nutrient aqueous extract, with its amylase, maltose, and glucose, etc., is called "beer wort." In the next stage, hops[1] are added for color, flavor and aroma. Sometimes roasted malt is added for additional color and flavor. The whole mass is then boiled to kill most contaminants.

After clarifying and cooling this mixture, the brewer's yeast (Saccharomyces cerevisiae) is added. During this time

---

[1]. Hops, *Humulus lupulus*, is cultivated for the papery scales of the female flower. These are dried and/or powdered for use.

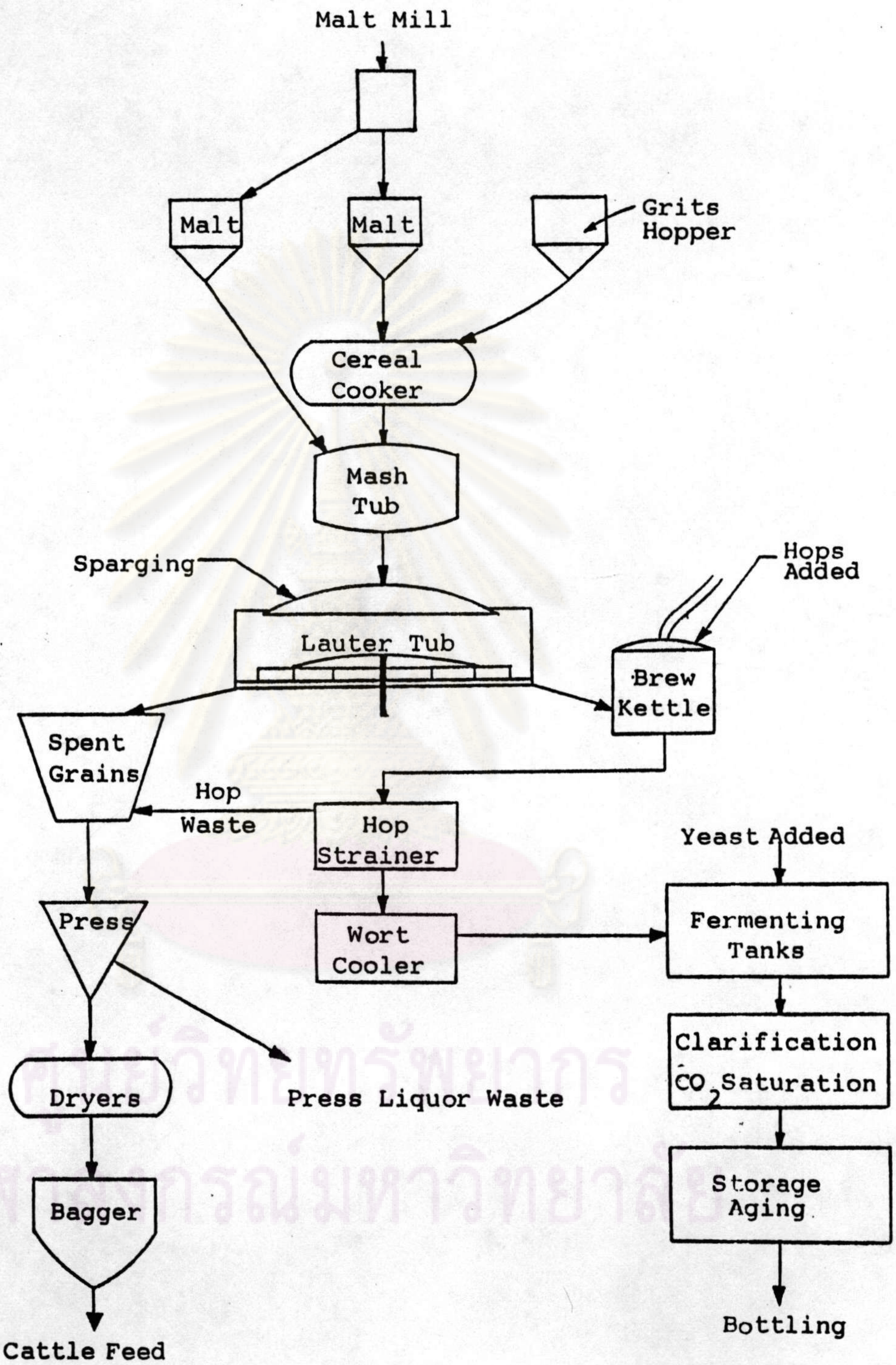

Fig.3.1 Flow diagram of a typical brewery operation (Lovan & Foree, 1974)

the yeast produces enzymes to break down the sugars and convert them principally into CO_2 and C_2H_5OH (carbon dioxide and ethanol or ethyl alcohol). After fermenting has been completed, the yeast cell is settled out from the beer solution. The beer is then aged ("lagered"[2]) in the pressure-controlled containers at a cool temperature. The final process is the clearing of the beer by filtration. Then it is carbonated in bottles and sold (Ford, 1971).

3.1.2 Sources of Pollution in a Brewery

3.1.2.1 Handling of spent grain and hop

From the lauter tub and hop strainer, the wet spent grains and hops pass to a press to squeeze out the liquid. This liquid plus any suspended solids not retained by the press is the press liquor waste. It is discharged directly into the waste pipe system. The mixture of spent hops with the spent grains is dried in steam-heated rotary dryers. Having a high fat and protein content, it makes excellent cattle and animal feed.

3.1.2.2 Brewhouse

In the brewhouse, there are two more large sources of pollution. These are last runnings and what is called under-wash water. After the straining of the lauter tub has been completed, a considerable amount of sludge is left on the under side of the strainer. This water used to be flushed to the drain before the next brew.

---

2. Lager is German for "to be stored".

3.1.2.3 Handling of yeast

The surplus yeast occurring in both the fermenting tanks and the lagering tanks constitutes a major source of pollution. From the point of view of drainage and for economic reasons, the yeast is worked up in such a way that the residue beer is recovered and returned to the process. This is done on a rotating vacuum filter in which the yeast is filtered on a bed of kieselguhr[3]. The filtered yeast, which contains 0.5 - 2% kieselguhr, is autolyzed and then pumped to the spent grains dryer, where the yeast is mixed with the spent grains and dried.

3.1.2.4 Cleaning, fermenting and largering tanks

In brewing process, the beer is fermented and lagered both in vertical and horizontal cylindrical tanks. The cleaning is started immediately after the tanks emptying. The organic load is due to yeast and beer which has fastened on the walls of the tanks. The discharge is acidic wastewater resulting from these polluting substances and acidic detergent used in the cleaning process.

3.1.2.5 Beer filtration

There are two Meta filters for beer filtration. In these filters pre-coating is done with the kieselguhr suspended in water. When the beer is then connected to the filter, a beer-water mixture is obtained which cannot be directly used. The

---

[3] kieselguhr is German meaning diatomaceous earth powder used for filter aid.

beer-water mixture with less than 40% beer content is led to the waste pipe system. A beer-water mixture comprising 40 - 75% beer goes to a special retainer tank while that with a concentration over 75% gas through bottling tanks to bottling. The beer-water mixture in the draw-off tank is metered continuously into the beer that goes to the filter. The procedure is similar when the filtration process is stopped and the remaining beer is pressed out of the filter with water.

3.1.2.6 Handling of kieselguhr

The kieselguhr in the Meta filters is not re-used. After completion of the filtering process, the used kieselguhr is flushed with water down into a large container from with the kieselguhr suspension is pumped to a 3-stage settling tank where the kieselguhr suspension is largely separated. The settling tanks are emptied once a week and the sludge is transported to the dump by tanker.

3.1.2.7 Bottle washing machines

In bottle washing, caustic and other alkaline detergent are used for cleaning agent. When bottles are cleaned, labels, label glue and remaining extract are released. Almost all of these labels are caught in the washing machines and removed from a brewery in solid form while the remaining labels leave the brewery together with glue and extract through the wastewater.

3.1.2.8 Bottling hall and pasteurization

The main source of pollution in the bottling hall is beer losses. This occurs primarily when the bottling machines are started, or from bottle breakage, dripping from filling pipes, foaming prior to capping and when bottling is stopped in the evening.

At the final step, a high temperature wastewater is caused to occur from the beer pasteurization process. Normally, however, the temperature does not exceed 40°C, at which it passes into the treatment plant.

3.2 General Properties of a Brewery Wastewater

Brewery wastewater is generally characterized by a very high concentration of dissolved organics, a moderately low concentration of suspended organics which can be removed by sedimentation, low nutrients, and high temperature (35°- 57°C). The widely fluctuating flow volume, organic loads and pH value are commonly found in brewery wastewater. The concentration of COD is as high as 8,000 mg/l and as low as 1000 mg/l. The relationship of BOD : COD varied between 0.2 and 0.9; approximately 70 to 80 percent of the COD is easily biodegradable. A wastewater with COD/BOD ratio near 2/1 is feasible for biological treatment (Jewell, Eckenfelder & Lavalier, 1971). Morever, toxic substances such as heavy metals, organic solvents, etc., are not included in wastewater from a brewery (Meyer, 1973). Table 3.1 specifies in somewhat more detail the polluting substances from various stages of the process.

Table 3.1

Polluting substances from different parts of a brewery (Meyer, 1973)

Source	Polluting substances
Mashing	Cellulose, sugars, amino acids, detergent
Straining	Spent grains, sugars, amino acids, detergent
Wort boiling	Hops, wort, detergent
Hop strainer	Spent hops, wort, detergent
Hot wort tank	Wort, detergent
Fermentation	Yeast, beer, detergent
Lagering	Yeast, sedimented protein, beer, detergent
Beer filtering	Kieselguhr, yeast, protein, beer, detergent
Bottling	Beer, glass, caps, detergent
Bottle washing machines	Beer extract, glass, labels, glue, oil, degreasing agent, detergent, caustic

3.3 Boon Rawd Brewery Wastewater

The Boon Rawd Brewery wastewater is a combined discharge from the brewery and the other plants, i.e., soda water and pure drinking water plants. The total volume of wastewater per day is now approximately 4500 m^3. A large portion, estimated 80%, arising from the bottle washing process and the beer pasteurization, is a very diluted wastewater (COD of approximately 80 mg/l). The remaining 20%, resulting from the brewing process, is a high concentrated wastewater having a COD of approximately 10,000 mg/l (the detail is describes on the previous item). All discharge is piped via a pump station to the treatment plant which is located in the brewery. The important characteristics of wastewater when passing into the treatment plant are summerized in Table 4.1 in the next chapter.

3.4 Literature Dealing with the UASB Process

3.4.1 UASB-Experiments with Industrial Wastes

The UASB-laboratory studies have been initially investigated in the Netherlands since 1971, with reactor varying in volume from 1 to 60 liters and in height from 0.2 to 1 m. Numerous results indicate successful treatment of a number of wastes with suggested design loading rates of 10 - 14 KgCOD/m^3-d corresponding to a maximum sludge loads in the range of 1 KgCOD/KgVSS-d. The most relevant results of these laboratory-phase experiments are summerized in Table 3.2 (Lettinga *et al.*, 1980).

Since 1976 the first pilot experiments have been carried out with sugar-beet wastes (Lettinga, 1980). Initially a 6 m^3 reactor with a height of 3 m was used. Later, 30 and 200 m^3 reactors were treated in order to obtain additional data for design of a full-scale plant. The results as summarized by Lettinga *et al.* (1980) are presented in Table 3.3.

In the period from 1966 to 1977, the Centrale Suiker Maatschappij (CSM) has carried out an intensive study on the UASB process treating the wastewater of her beet sugar factories in the Netherland. The research has been developed from lab-scale to

Table 3.2 Results of some laboratory UASB experiments with various types of wastes[a] (Lettinga *et al.*, 1980).

	Waste solution			Maximum COD load applied					UASB reactor		
	COD										
Origin	Total (mg/l)	Dissolved[b] (%)	VFA	Space load (Kg/m^3-d)	Sludge load (Kg/KgVSS-d)	HRT (h)	COD reduction (%)	Sludge yield factor (Kg/KgCOD)	Temp. (°C)	Volume (liter)	Height (cm)
Sugar-beet sap, unsoured	5000 - 6000	95	nil	4 - 5 (diss.)	0.5 - 0.8	48 - 24	95	0.15	30	61	105
Sugar-beet sap, soured (closed circuit)[c]	6000 - 9500	80 - 60	4000 - 5000	8 - 10 (diss.)			84 - 95 (diss.)	0.09 - 0.07 (diss.)	30	18	70
				10 - 14 (total)	0.7 - 1.1	12 - 24	65 - 75 (total)	0.1 (total)		30	100
Sugar-beet sap, soured (2-stage)	6000 - 9000	95	5400 - 8000	8 - 9 (2nd stage)	0.8 - 1.0 (2nd stage)	24	90 - 97	0.04 - 0.03	30	18	70
Bean blanching	5200	90	500 - 1500	8 - 10	0.6 - 0.8	13 - 15	90 - 95	-	30	2.7	30
Sauerkraut	10000 - 20000	97	400 - 1500	8 - 9	0.8 - 1.2	24	88 - 93	0.05 - 0.07	30	2.7	30
Dairy (skimmed milk)	1500	75	nil	7 - 8	0.4 - 0.6	5	90	0.18[d]	30	18	70

a Values mentioned for the COD load concern the maximum values that could be applied in the specific experiment.

b COD remaining after filtration over a filter SS 520 b.

c Experiments conducted in a closed simulated wastewater circuit : a known amount of sugar-beet sap solution is supplied continuously in the circuit water.

d Higher values are obtained in case of substrate precipitation (i.e. at a pH fall or in case of overloading).

Table 3.3 Results obtained in a 6-m^3 pilot-plant and 200 m^3 full-scale plant experiments (Lettinga *et al.*, 1980).

Type of waste	UASB reactor (m^3)	Influent characteristics		Maximum loading rate applied		Treatment efficiency based on			
		COD range[a] (mg/l)	Soured (%)	Organic (KgCOD/m^3-d)	Hydraulic (m^3/m^3-d)	Temp. (°C)	$E_{COD_{cen.}}$ [b] (%)	$E_{COD_{diss.}}$ [c] (%)	$E_{COD_{cen.}}$ (%)
Liquid sugar	6	4000 - 6000	15 - 25	20 - 25	4	28 - 32	92 - 95	93 - 98	-
Campaign waste	6	3500 - 4000	75	30 - 32	4 - 6	28 - 32	95 - 80	95 - 98	-
Campaign waste	200	4000 - 5200	70 - 90	14 - 16	3 - 4	30 - 34	87 - 95	-	90 - 95
Potato processing	6	2000 - 5000	25	3 - 5	1.2	19	95(92)[d]	-	94
(lime used as	6	2000 - 5000	30	10 - 15	3	26	95(89)	-	98
neutralizing	6	2000 - 5000	12	15 - 18	4	30	95(89)	-	97
agent)	6	4000 -16500	8	25 - 45	6 - 7	35	93(89)	-	96

a COD value based on centrifugated samples.

b $E_{COD_{cen}}$: based on centrifuged effluent samples and raw influent COD values.

c $E_{COD_{diss.}}$: based on centrifuged influent COD values and effluent COD values determined after flocculation of the sample with 200 mg Fe^{3+}/l.

d Values in parentheses refer to effluent samples that have been allowed to settle for 30 minutes.

full-scale experiments. Some of the main results of the operation are listed in Table 3.4 (Pette *et al.*, 1980).

The study of fluid flow pattern in a 30-m^3 UASB reactor (height 6 m, i.d. 2.6 m) was done by means of stimulus-response experiments with a Li^+ tracer mixed in a sugar beet wastewater. It was concluded that 60 m^3 gas/d were sufficient to provide good mixing and also that the height of the sludge bed should be 2-3 m. From the process performance, results showed that 800 - 2000 mgTOC/l of influent, 5.5 KgTOC/m^3-d of organic loadings, and 6 - 8 m^3/m^3-d of hydraulic loadings, could be treated with efficiencies of about 95% at 30°C. These results were later used to design the 200 m^3 full-scale reactor; with a diameter of 7.5 m and height 4.5 m (Heertjes & Van Der Meer 1978; Heertjes & Knijvenhoven, 1982).

The feasibility of using a UASB reactor for denitrification was investigated in 24- and 41-liter reactor (both approximately 1 m in height) by Lettinga *et al.* (1980). Acetate solution as well as alcoholic wastes have been used as the carbon source. The main results are contained in Table 3.5. Very satisfactory results were obtained with respected to nitrate and/or COD reduction, even at extremely high organic and hydraulic loading rates. It was reported that, with alcoholic waste, a granular sludge (pellets of 1 - 3 mm in diameter) developed in the course of 6 - 8 weeks.

Christensen, Gerick & Eblen (1984) adapted the 2200 m^3 UASB reactor to meet an increased potato processing capacity of a factory in the USA. At steady-state operation, the COD removal rate

Table 3.4 Treatment Parameters - CSM Results (Pette *et al.*, 1980).

Parameters	6 m^3 Pilot Plant		30 m^3 Pilot plant		200 m^3 Industrial Plant
	Liquid Sugar Waste May '75	Beet Sugar Waste Nov '75	Beet Sugar Waste Nov '76	Liquid Sugar Waste May '77	Beet Sugar Waste Dec '77
pH	6.5	7.4	7.0	7.1	7.1
Temperatures (°C)	32	32	30	33	30
COD Load (Kg/m^3)	4.0	3.6	2.0	3.5	4.2
Hydraulic Retention Time (h)	6.0	2.6	4.4	9.0	7.1
COD Capacity (Kg/m^3-d)	16	32	11	11	14
COD Reduction (%)	91	75	63	93	90
Total Sludge (KgSS)	240	360	350	1000	6000
VSS in Sludge (%)	75	66	77	84	35
Sludge Load (KgCOD/KgVSS-d)	0.5	0.8	1.3	0.4	1.3
Gas Production (m^3/m^3-d)	7.4		3.0	4.5	4.7
Gas Production (m^3/h)	1.9		3.8	5.6	39.2
Methane Component (%)	70	90	90	72	83

Table 3.5 Results of denitrification experiments using the USB process (Lettinga *et al.*, 1980).

COD load		Influent						
Space load (Kg/m^3-d)	Sludge load (Kg/Kg-d)	COD (mg/l)	NO_3^--N (mg/l)	HRT (h)	COD reduction (%)	NO_3^--N reduction (%)	Amount of sludge in reactor (g)	TS in sludge bed (g/l)
1) Experiments with acetate as C source[a]								
5.0	0.3 - 0.33	288	68	1.5	98	100	380	20
4.8	0.3 - 0.31	194	44	0.97	90	99	388	25 - 22
11.1	0.6 - 0.65	178	36	0.38	55	42	450	42 - 33
2) Experiments with alcoholic-waste[b] as C source[c]								
19.7	1.1	2600	858	3.2	98	89	700	60
18.8	1.1	1590	426	2.0	97	96	650	47
19.7	1.1	495	163	0.6	93	85	700	31
19.7	1.1	370	123	0.5	91	82	700	-
19.7	1.8	270	89	0.3	92	77	420	-

a USB reactor : 31.2 liter volume; d_1 = 19 cm, 110 cm height; stirring : 2 sec at 45 rpm every 1 - 2 min.

b Composition of the undiluted waste; methanol : 380 gCOD/l; ethanol : 201 gCOD/l; propanol : 81 gCOD/l; butanol : 76 gCOD/l.

c USB reactor : 41 liter volume; d_1 = 19 cm; 140 cm height; stirring : 6 sec at 21 rpm every 30 - 45 sec.

was reported to be 85% while the organic loading rate and HRT were 3 KgCOD/m^3-d and 21.2 hours, respectively. The 2500 mgCOD/l of waste stream was fed at 35°C.

Sayed, Zeeuw & Lettinga (1984) studied the feasibility of using the UASB process for the single-step anaerobic treatment of slaughterhouse waste, which contained approximately 50% insoluble suspended COD. The 30-m^3 UASB reactor could handle organic space loads up to 3.5 KgCOD/m^3-d at an HRT of 8 hr and temperature as low as 20°C. A treatment efficiency of up to 70% on a total COD basis, 90% on a soluble COD basis, and 95% on a soluble BOD basis was smoothly approached. The biogas production of 0.28 Nm^3/KgCOD removed contained 65 - 75% of methane.

A new hybrid reactor, the upflow blanket filter (UBF), which combined a UASB reactor in the bottom with an anaerobic filter (AF) in the upper one-third of the reactor volume was studied by Guiot and Van Den Berg (1984). The lab-scale UBF reactor (4.25 l) was tested by a synthetic soluble sugar waste of 2500 mgCOD/l. The reactor was operated at 27°C and at loading rates varying from 5 to 51 KgCOD/m^3-d. It was found that conversion was over 93% with loading up to 26 KgCOD/m^3-d. At higher loading rate, conversion decreased rapidly.

In 1984, there were over 50 full-scale UASB reactors installed in several countries throughout the world (see Table 3.6). As can be seen, many types of wastewater can be treated by the UASB system in a very efficient way. The La Cross, Wisconsin, UASB reactor which treats wastes from a brewery, is the largest in the world

Table 3.6 UASB-plants installed and commissioned by July 1985 (Lettinga *et al.*, 1985).

Type of wastewater	Number of plants	Country of installation	Number of plants in country cited	Design* capacity (KgCOD/m^3-d)	reactor volume
Sugarbeet	12	Netherlands	7	12.5-17	200-1700
		Germany	2	9,12	2300,1500
		Austria	1	8	3000
		Spain	2		approx.1000
Liquid sugar	1	Netherlands	1	17	30
Potato processing	10	Netherlands	8	5-11	240-1500
		USA	1	6	2200
		Switzerland	1	8,5	600
Potato starch	3	Netherlands	2	8.5,15	1700,5500
		USA	1	11	1800
Maize starch	1	Netherlands	1	10-12	900
Wheat starch	3	Netherlands	1	7	500
		Ireland	1	9	2200
		Australia	1	11	4200
Barley starch	1	Finland	1	8	410
Alcohol	3	Netherlands	1	16	700
		Germany	1	9	2300
		USA	1	9-10	2100
Yeast	2	USA	2	12,9	4400,1800
Brewery	2	USA	1	14	4600
		Netherlands	1	6-18(24°C)	1400
Shell fish	1	Netherlands	1	10	2x50
Slaughterhouse	1	Netherlands	1	6-7	650
Dairy	1	Canada	1	6-8	450
Paper	3	Netherlands	3	8-10	1000,740
				4(20°C)	740
				5-6(25°C)	2200
Vegetable canning	2	Netherlands	1	10	375
		USA	1	11	500
White spirit	12	Thailand	12	15	3000
Chemicals	1	Netherlands	1	7	1250
Candy	2	Netherlands	2	11,13	100,50

* at treatment temperature 30 - 35°C, unless cited otherwise.

(Lettinga *et al.*, 1984).

Since 1983 the achievement of small-scale UASB experiments (30-l and 50-m^3 reactors performed at 30°C) with the Paper and Board Mill wastewater were presented in the Netherlands. The COD concentration of wastewater was in the range of 1600 - 2000 mg/l. In both cases, loading up to 20 KgCOD/m^3-d or more could be handled. COD removal was 70%, even when the HRT was only 2.5 hours. After good results obtained, further investigation were started on 70-m^3 and 1000-m^3 UASB reactors in 1983. These plants were working satisfactorily (Habets & Knelissen, 1985).

The feasibility of the UASB process for treatment of potato starch wastewater at low ambient temperatures was studied by operating two 5.65-l reactors at 14°C and 20°C, respectively. The organic space loading rates achieved in these lab-scale reactors were 3 KgCOD/m^3-d at 14°C and 4 - 5 KgCOD/m^3-d at 20°C (Korter and Lettinga, 1985).

Recently the operation of UASB reactor containing thermophilic granular sludge cultivated on synthetic feed has been investigated. The experiment has been carried out in a 5.75-l (9 cm i.d) reactor. The results of the experiment with volatile fatty acid as the main substrates are summarized in Table 3.7 (Wiegant & Lettinga, 1985).

Cail and Balford (1985) studied the development of granulation, on high strength cane juice stillage (COD ≈ 7.5 g/l), in an Upflow Floc digester and an UASB. They concluded the use of synthetic polyelectrolytes in the UF digester during treatment

Table 3.7 Process parameters of UASB reactors containing thermophilic granular sludge cultivated on sucrose or glucose, with substrates consisting mainly of volatile fatty acids (Wiegant & Lettinga, 1985).

Substrate	Acetate and yeast extract	Acids[a] + sucrose	Acid[a] and yeast extract
Concentration (KgCOD/m3)	1.41	8.02	14.65[d]
VFA(KgCOD/m3)	1.35	6.48	13.32
non-VFA(KgCOD/m3)	0.06	1.54	1.33
Hydraulic retention time(h)	2.1	5.7	3.2
Organic loading rate (KgCOD/m3-d)	16.0	35	104
Treatment efficiency[b](%)	98.9	84.5	77.6
Duration[c] (days)	31	105	182

a The acids were acetate, propionate, and butyrate in a 1:1:1 (w/v)

b This is L effluent VFA COD/L influent COD*100%.

c With duration the period of continuous feeding with the substrate mentioned is meant, not the period of maintenance of the process parameters given.

d These parameters were measured in a 0.70 l UASB reactor.

Table 3.8 Main results obtained in a 6 m3 UASB plant with raw domestic sewage as influent (temperature range 9.5 - 19°C, liquid-retention time 8 hours) (Lettinga *et al.*, 1984).

Measurement	Week number		
	1-11	16-22	24-26
Temperature (°C)	19-15	11-12	9.5-10
Effluent $COD_{filter.}$ (mg/l)	100-200	150-175	175-250
COD reduction $(\%)_{filter.effl.}$	65-80	55-70	55
COD reduction $(\%)_{raw\ effl.}$	40-55	30-50	30
CH_4 production ($m3/KgCOD_{infl.}$)	0.130	0.090	0.050
Excess sludge production ($KgDS/KgCOD_{infl.}$)	0.195	0.172	0.271

resulted in a more rapid accumulation of biomass, allowing a bit higher loading to be achieved and promoted the earlier development of granular sludge, compared to the UASB reactor.

The experiment of the 21-l laboratory UASB reactor with the brewery wastewater had been conducted at 35°C. It was reported that granulation was completely achieved within 70 days. After granulation, the volumetric COD loading rate was acheieved up to 32 KgCOD/m^3-d with COD removal of 90% (Wu *et al.*, 1985).

To investigate the feasibility of the meat packing wastewater treatment with UASB at 15° - 25°C, Zheng and Wu (1985) carried out both a 33.8-l of lab-scale and 21-m^3 of pilot-scale experiments. The results of the two experiments were nearly the same. The efficiency of treatment was between 77 - 83% when loading and HRT were in the range of 2 - 9 KgCOD/m^3-d and 4 - 12 hr, respectively.

The surveyed papers concerning the UASB-experimental works here in Thailand were the following :

Pang (1987) made comparison of the process performance with respect to the removal of solid between a UASB reactor having Inclined Tube Settler (UASB/ITS) and that of conventional UASB reactor. Two 10-L laboratory reactors (height 65 cm; i.d 14 cm) were used to treat the brewery wastewater from the Thai Amarit Brewery, with COD of about 4000 mg/l and operating temperature 35 ± 1 °C. In both reactors, the resulting COD removal was higher than 95% when the organic loading rate was up to 10 KgCOD/m^3-d at 12 h HRT. It was concluded that the UASB/ITS was 5% more effective for solid removal than a UASB reactor.

The two-stage pilot-scale UASB reactor with the volume of 106 liters (height 2.75 m, i.d 6 inches) was used to treat the actual wastewater from the Greenspot (Thailand) factory. The wastewater contained 1200 - 1500 mgCOD/l and was fed at ambient temperature. The experiment gave the results, viz. 89 - 94% COD reduction, 0.4 - 4.8 KgCOD/m^3-d organic loading and 4 - 48 hr hydraulic retention times (Pitayathorn, 1986).

Another research was on a 250-l UASB reactor (height 3.85 m; i.d 29.2 cm) treating the same wastewater except for residual soybeans being added in 3 fractions; corresponding to 13784, 28898 and 43734 mgCOD/l of wastewater. The resulting COD removal efficiencies were 95%, 75% and 58.4% while the organic loading rates were 2.76, 5.83 and 8.74 KgCOD/m^3-d, operated at 5 d HRT. Biogas production was 275.8, 423.4 and 561.0 l/d containing 61.8%, 56.5% and 46.7% of methane (Chitcharoongkiat, 1986).

A recent paper dealing with a successful start-up of the first full-scale 3000-m^3 UASB reactor in Buri Ram Distillery Plant of the Surathip Group was published in early 1990. The success was due to the anaerobic fixed bed and the UASB pilot-plant experiences. The pilot-scale data obtained indicated that COD removal of the wastewater with a COD of ≈ 50 - 60 g/l, consisting of slop and bottle washing water in the ratio 1 : 1, was about 50%. The UASB process which used intermittent feeding resulted in an easier increase of the COD loading from 3 - 7 KgCOD/m^3-d and a better granulation improved, compared to the continuous feeding UASB reactor. Regarding the fixed bed reactor, it revealed a quicker start-up result than those of the UASB reactors and a maximum of COD loading to 10 $KgCOD/m^3$-d. These results will be further used to start-up the other full-scale UASB reactors of the Surathip Distillery chains in the near future (Verink *et al.*, 1990).

3.4.2 UASB Experiments with Raw Domestic Sewage

Since 1976 there have been intensive investigations on the UASB treatment of raw domestic sewage. The first experiment was conducted in a 120 l UASB reactor with the wastewater containing ≥ 400 mgCOD/l, and operated at 12 h HRT. Within the temperature range from 5° to 10°C, the COD removal efficiencies of 65 - 85% were reported. Sugar beet waste adapted granular sludge was used as seed (Lettinga *et al.*, 1980).

In a 6-m^3 pilot plant (reactor height 3 m) experiment for raw sewage with a COD of 400 mg/l using digested sewage sludge as the seed, at a temperature of 20°C with a HRT of 22 hours, COD removal efficiency of 60 - 80% was obtained. Slight mixing by gas recirculation was applied (Lettinga *et al.*, 1980).

Lettinga *et al.* (1983) presented pilot-scale data for the upflow anaerobic sludge blanket treating domestic wastewater. At hydraulic retention times as low as 12 hours, 65 - 85% COD reduction was reported; but with heavy rainfall (i.e., low influence CODs), COD reduction dropped to 50 - 70%, and at very low CODs, to less than 50%. Over the course of the experiments, the average total COD concentration was 163.2 mg/l.

Lettinga *et al.* (1984) reported the results of experiments with raw domestic sewage at lower temperatures and the results are summarized in Table 3.8.

Fernandes, Cantwell & Mosey (1985) concluded that the performance data on two small UASB reactors treating settled domestic wastewater obtained at the Water Research Centre, Stevenage Laboratory, essentially confirmed the studies by Lettinga and others at the University of Wageningen. Anaerobic treatment removed 50 to 80% of the BOD and SS from settled wastewater at hydraulic retention periods of 3 to 12 h at 20°C, with only minimal production of sludge.

Results obtained in a 50-m^3 UASB with raw domestic sewage in Cali, Colombia, have shown a treatment efficiency of 60 - 80% despite the fact that the wastewater COD was less than 300 mg/l and the wastewater temperature was around 26° - 28°C (Lettinga *et al.*, 1984).