Chapter 5

Results and Discussion

5.1 Start-up

The UASB reactor was initially with anaerobic sludge with an amount of 17 $KgSS/m^3$ (50% VSS). The initial organic and the hydraulic loadings applied were kept between 1 - 2 $KgCOD/m^3$-d and 0.1 - 0.3 m^3/m^2-h, respectively. Granular sludge was first observed on the 12th day. The diameter of the granules varies from 0.05 to 8 mm. Microscopic examination using Scanning Electron Microscope (SEM) indicated that the granules consisted of both filamentous and rod shape granules as shown in Fig 5.1.

The sludge profile in the reactor during the start-up period is illustrated in Fig. 5.2. After 35 days, the TSS and TVSS concentration in the reactor (Fig. 5.3) were approximately 5000 g and 2300 g, respectively.

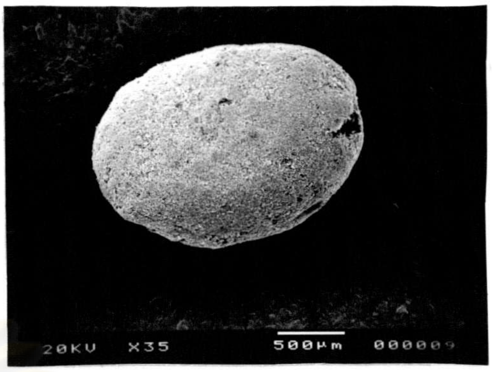
5.2 Performance of the Reactor

5.2.1 COD Removal

The COD removal is shown in Fig. 5.4. At the beginning of each HRT's experiment, the influent COD concentration used was about 500 g/m^3, and then increased gradually up to 2000 g/m^3. The experimental results revealed that the COD removal

Filamentous granule

SEM : JEOL - Bangkok

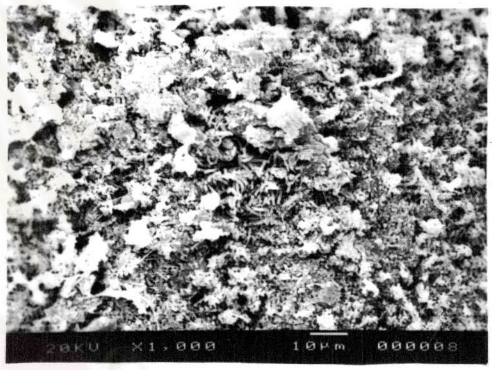


Rod - type granule

SEM : JEOL - Bangkok

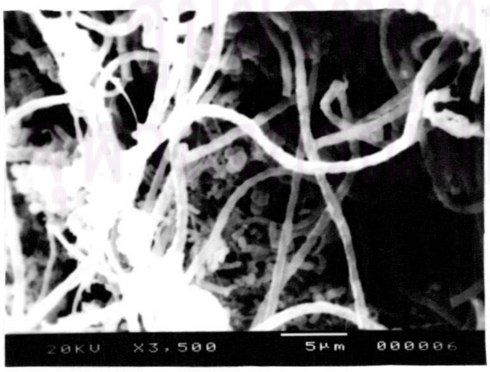
Filamentous granule

SEM : JEOL - Bangkok



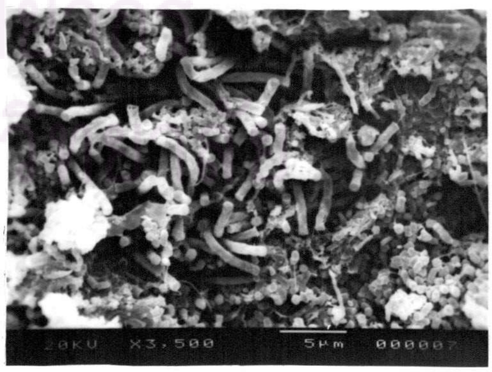
Rod - type granule

SEM : JEOL - Bangkok



Filamentous granule

SEM : JEOL - Bangkok



Rod - type granule

SEM : JEOL - Bangkok

Fig.5.1 SEM of the Filamentous granule and the Rod - type granule in the UASB reactor.

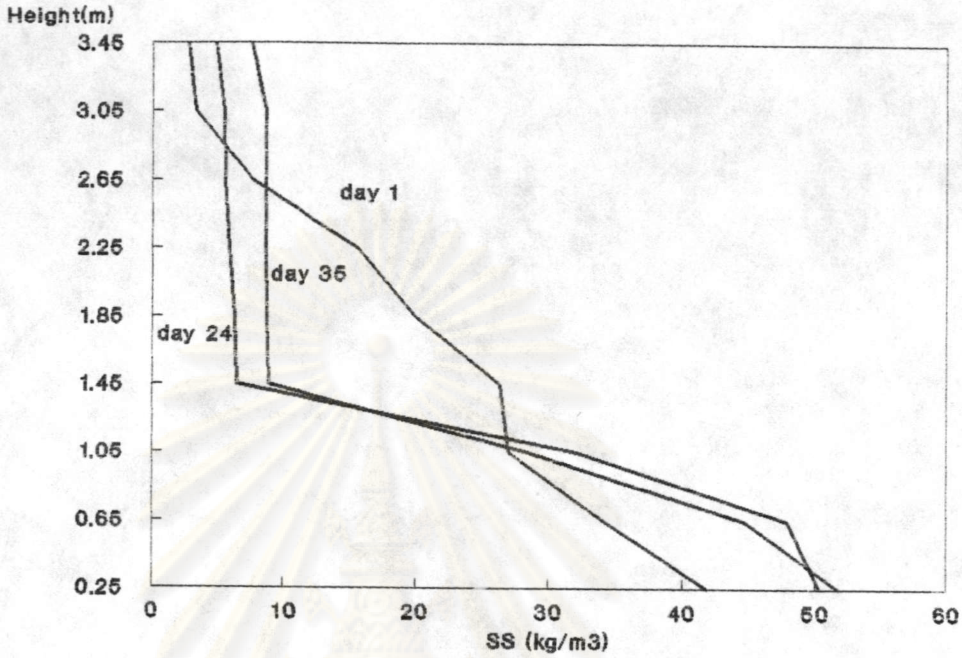


Fig.5.2 Sludge Profile during thestart-up period at day 1, 24, and 35.

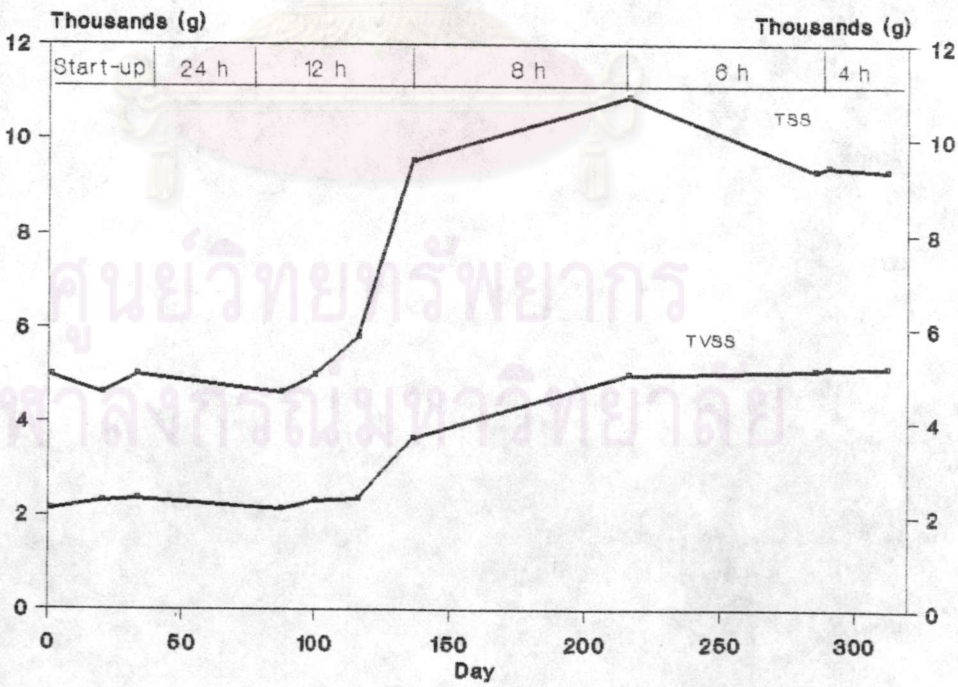


Fig.5.3 TSS and TVSS in UASB reactor.

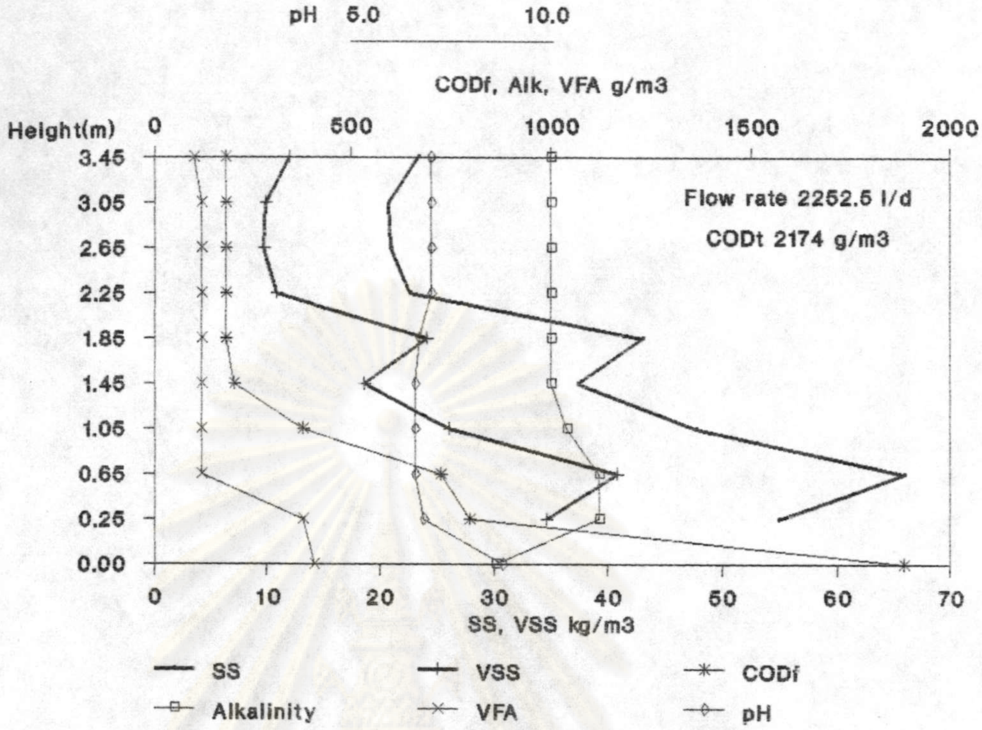


Fig.5.13 UASB profile at HRT 4 hr

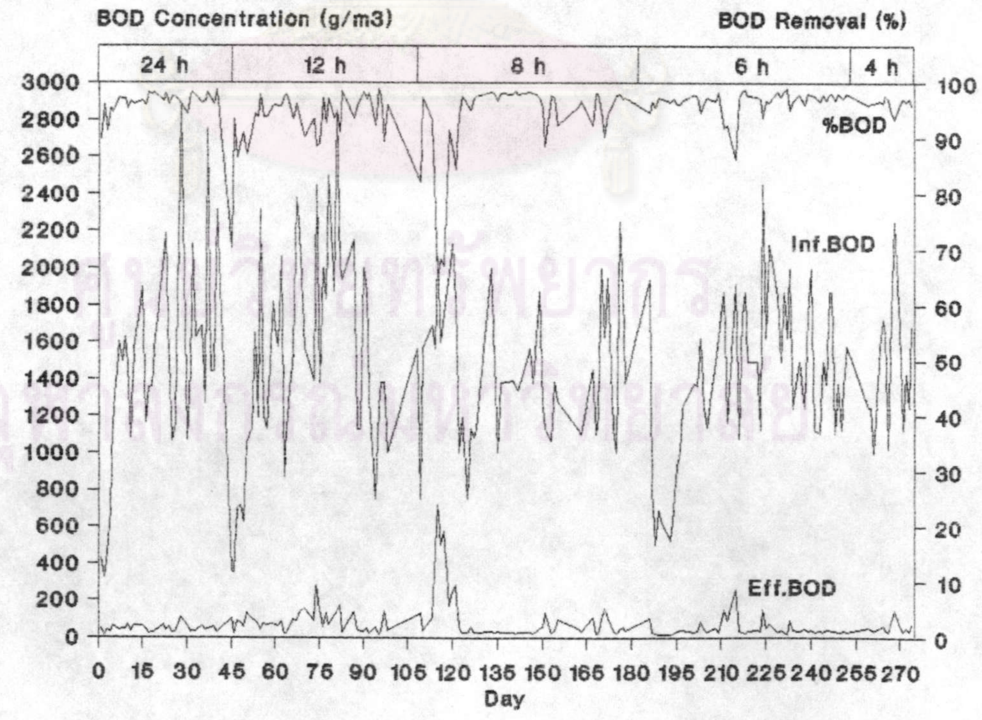


Fig.5.14 BOD Concentration and Efficiency during the experimental period

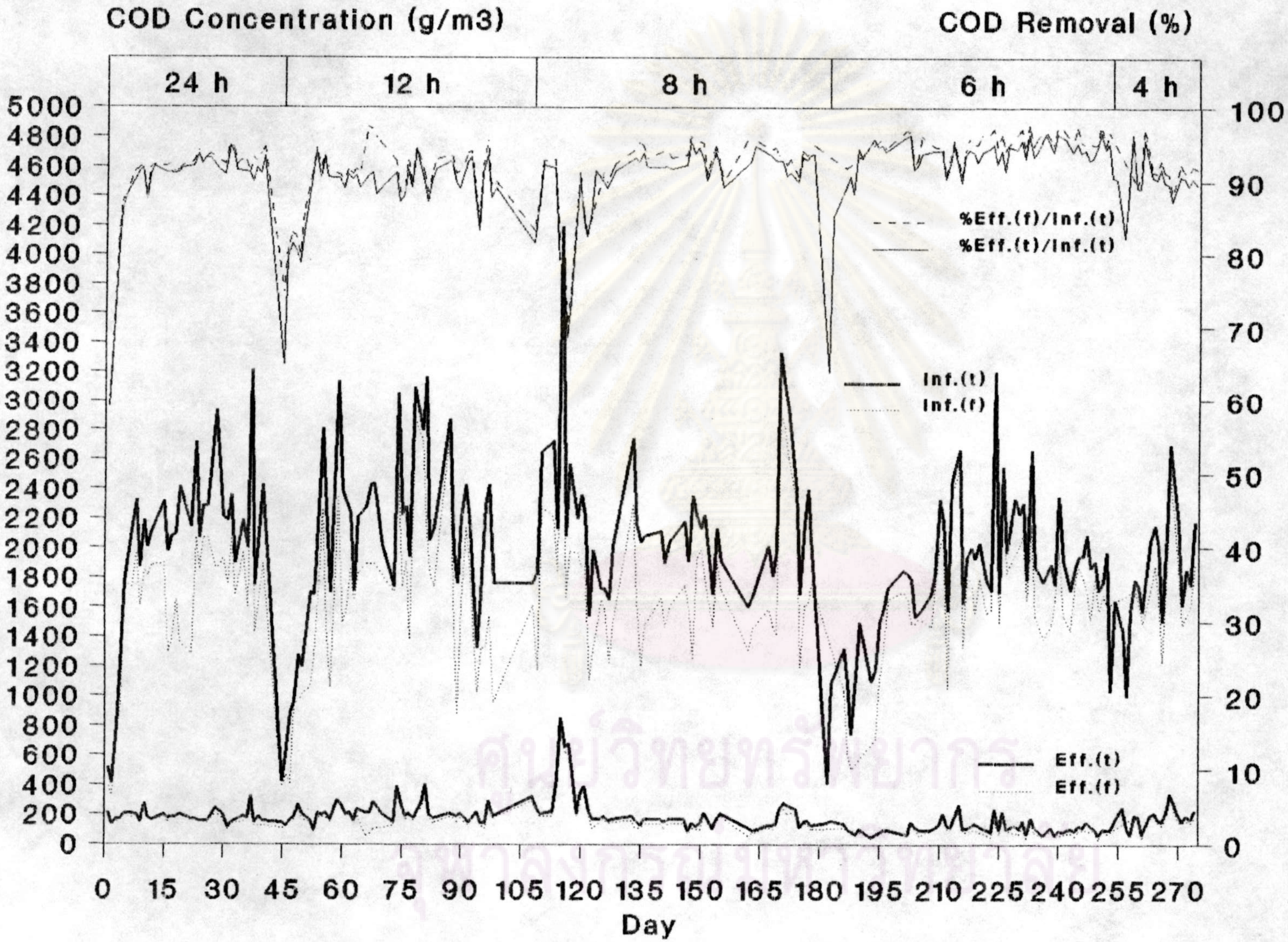


Fig.5.4 COD concentration and Efficiency with Time

increased rapidly from 60 - 70% to 90% or higher within one week. The reactor reached steady state conditions in not more than one week for every HRT used.

5.2.1.1 <u>COD Removal with Hydraulic Retention Time (HRT)</u>

The average COD removal efficiencies at various HRT's are shown in Table 5.1 and Fig. 5.5. The total COD (unfiltered) and soluble COD (filtered) removals at HRT's of 4 to 24 hrs were ranged from 90 to 94% and 91 to 95%, respectively. While the treatment efficiencies were still high, the HRT's could be reduced to as short as 4 hrs. This is due partly to suitable temperature of the system. The reactor was operated under ambient conditions and fed with the influent whose temperature range from 34° to 42°C (see Table 4.2). This range of temperature was best suit for mesophilic

Table 5.1

COD removal efficiency VS HRT's and organic loading.

Period* (day)	HRT (hr)	Organic Loading Rate	Influent COD		Effluent COD		COD Reduction**	
			Total	Filtered	Total	Filtered	Unfiltered	Filtered
9-40	24	2.2	2233	1790	183	163	91.8	92.6
52-98	12	4.5	2243	1747	214	180	90.4	91.9
123-178	8	6.4	2119	1710	162	136	92.4	93.6
209-252	6	8.1	2030	1787	121	95	94.1	95.4
263-274	4	12.4	2009	1750	202	177	90.0	91.2

* The interval was started at the day the incoming COD was up to 2000 g/m^3 and ≥ 90% of COD eliminated

** Filtered :COD reduction based on filtered effluent and raw influent

Unfiltered :COD reduction based on raw effluent and raw influent

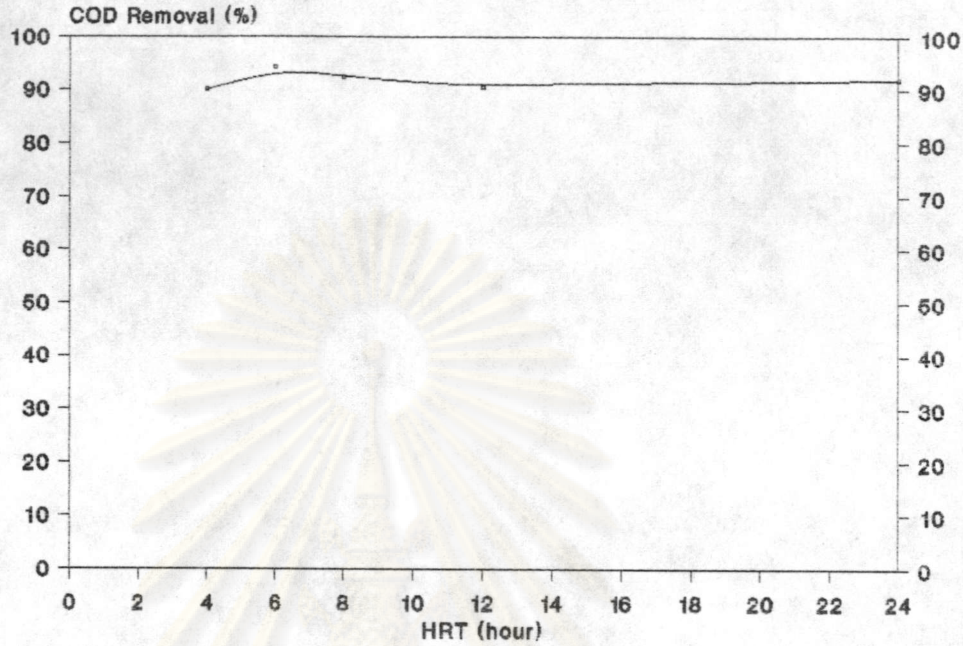


Fig.5.5 % Total COD Removal vs HRT

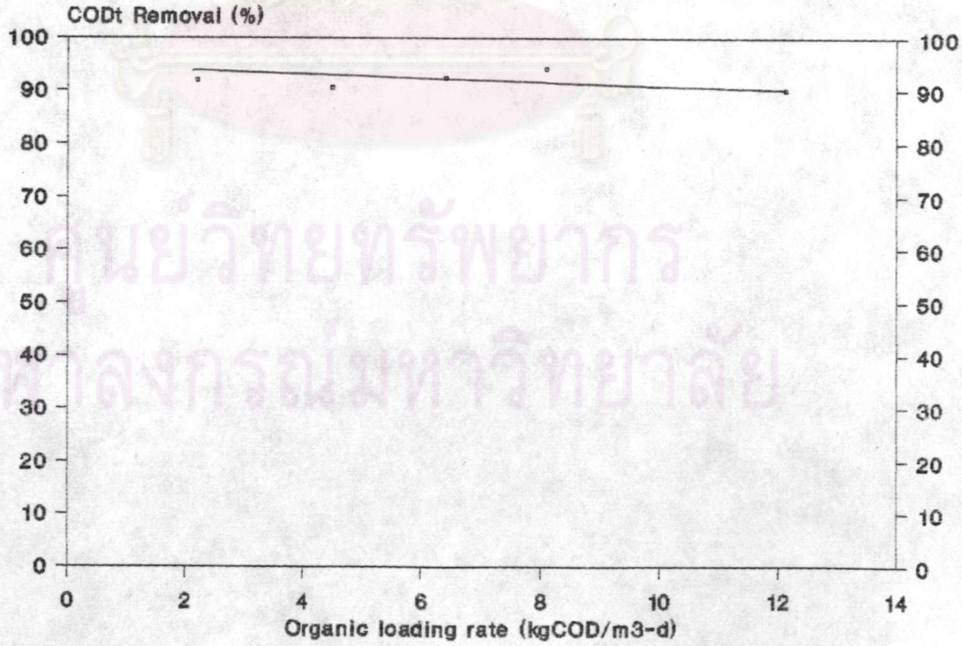


Fig.5.6 Total COD Removal Efficiency vary with Organic loading rate

bacterial growth and activity (Lettinga *et al.*, 1984). By increasing the digestion temperature, significant reduction in retention time required to obtain 90% digestion could be achieved (Fair and Moore., 1973).

5.2.1.2 COD removal with Organic Loading Rate

The relationship between organic loading and COD removal is shown in Table 5.1 and Fig. 5.6. The total COD removal efficiency of 90 - 94% could be achieved over a wide range of organic loading rates from 2.2 to 12.4 kgCOD/m^3-d. The COD removal efficiency decreased slightly with an increase in organic loading. The load of up to 12.4 kgCOD/m^3/d could still be well accomodated by this system. This indicated an efficient performance of the granular sludge retained in the reactor.

5.2.1.3 COD Removal with Sludge Retention Time (SRT)

The relationship between sludge retention time and COD removal is shown in Fig. 5.7. The sludge retention times in the reactor range from 67.8 days to 826 days. It can be seen that the total COD removal efficiency increased with SRT and was always 90% or more even at a low SRT of 67.8 days. The total amount of sludge retained in the reactor at the end of the experiment was 9300 gTSS and 5100 gTVSS (Fig. 5.3), which corresponded to 37 kgSS/m^3 and 20 kgVSS/m^3, respectively. These considerable amounts of sludge can be retained in the reactor even at low SRT of 67.8 d and HRT of 4 h. By observation, the settleability of this granular-type sludge was excellent.

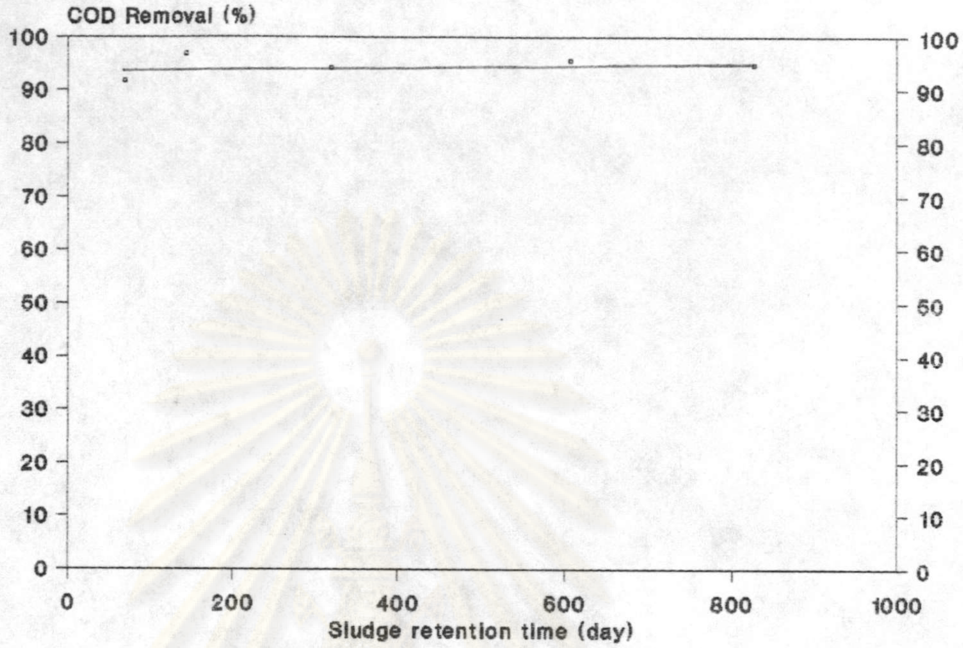


Fig.5.7 %Total COD Removal vs Sludge Retention Time

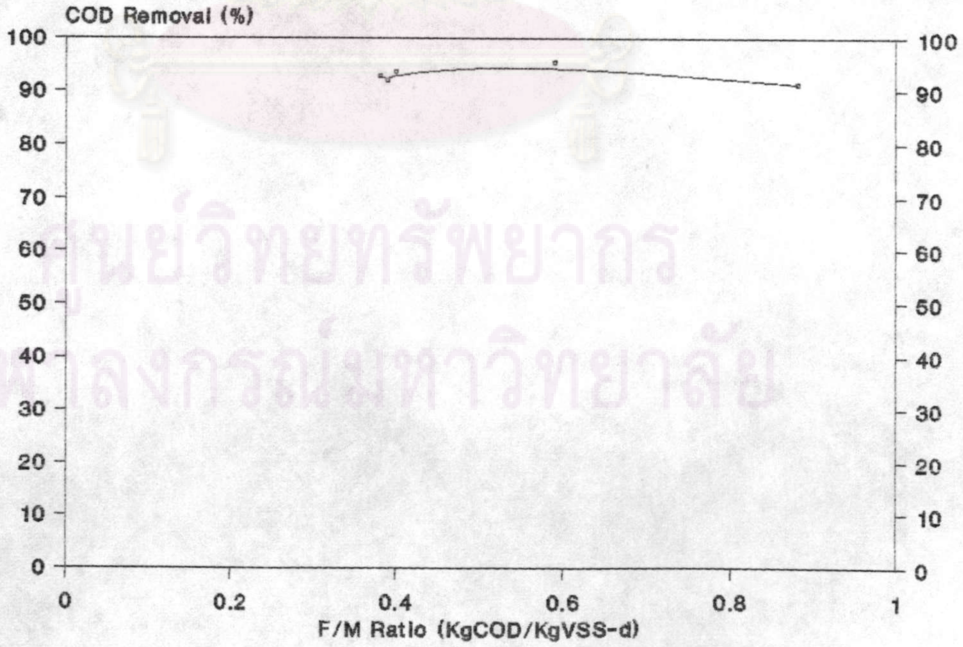


Fig.5.8 %Total COD Removal vs F/M Ratio

5.2.1.4 COD Removal with Food to Microorganisms (F/M) Ratio

The effect of F/M ratio on COD removal is shown in Fig. 5.8. The food-to-microorganisms ratio was calculated on the basis of the COD loading applied and the amount of sludge that was measured at the end of each run of HRT's. The COD removal effiency in the F/M ratio range used in this experiment was always high. It varied from 90 to 94% while the F/M value varied from 0.35 to 0.95 KgCOD/KgVSS-d.

5.2.1.5 COD Removal with Height

The soluble COD removal efficiency at various height at HRT of 24, 12, 8, 6 and 4 hours are shown in Fig. 5.9 to 5.13. The initial COD removal of about 60 - 70% took place at in the bottom 25 cm and increased to 90% or more at the height of less than about 1.5 m. There was very little improvement in COD removal efficiency at greater heights. A similar result has been reported by Lovan (1971) who conducted the anaerobic filter experiment with brewery wastewater and found that greater than 90% COD removal efficiency was accomplished in the bottom 6 inches of the filter column (72" height, 6" i.d).

5.2.2 BOD Removal

The average BOD removal efficiency at various HRT's are presented in Table 5.2 and Fig. 5.14.

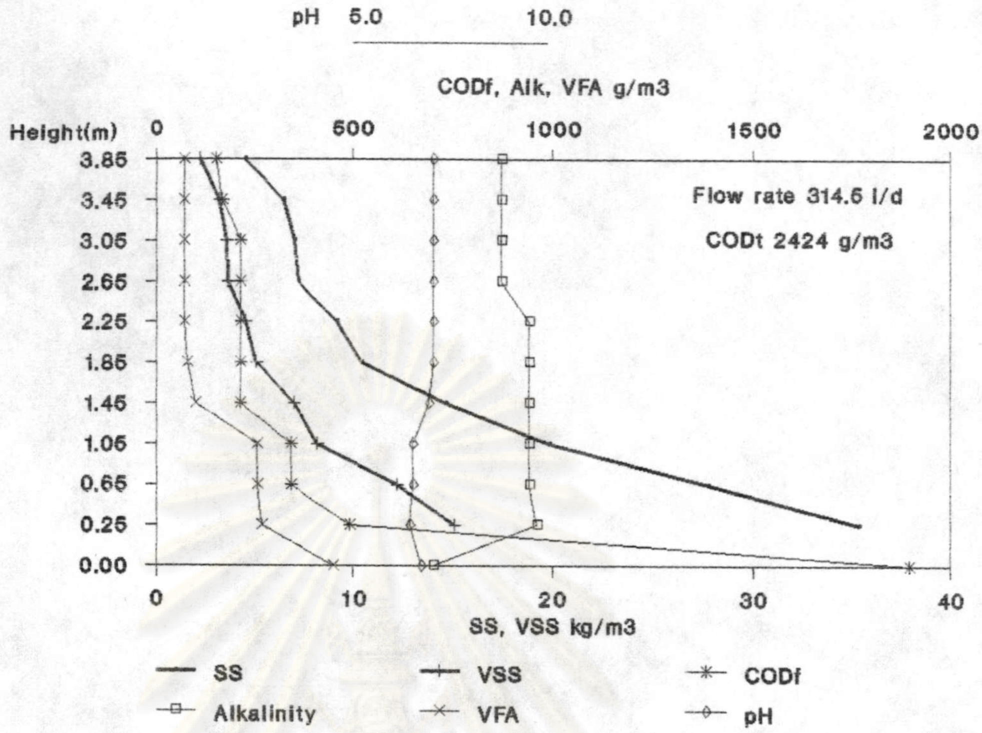


Fig.5.9 UASB profile at HRT 24 hr

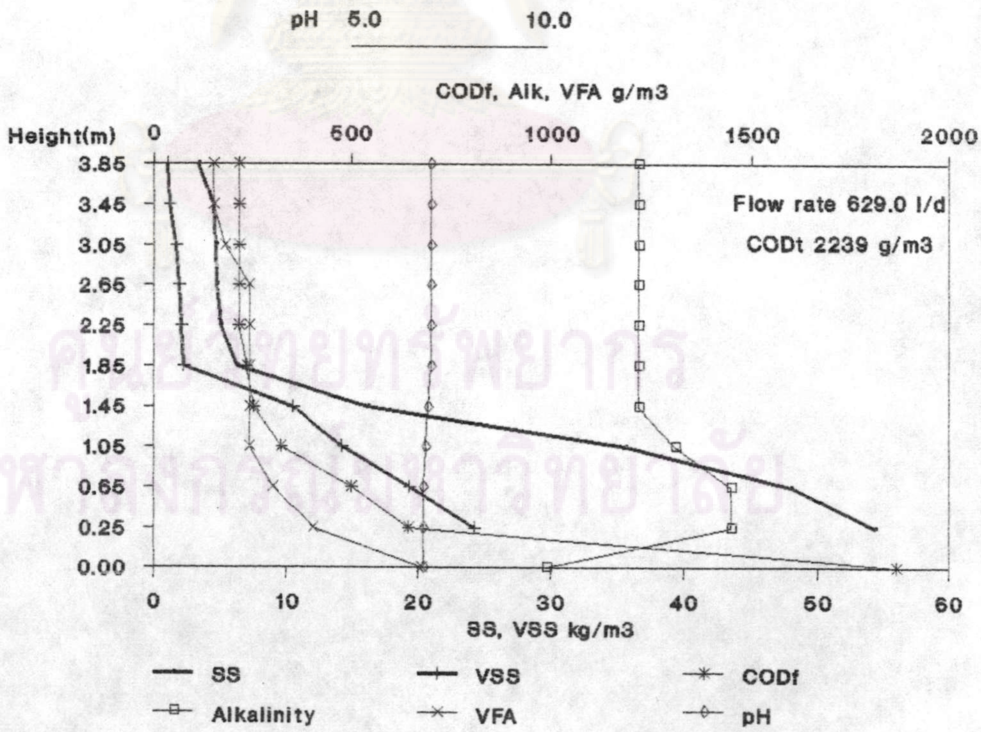


Fig.5.10 UASB profile at HRT 12 hr

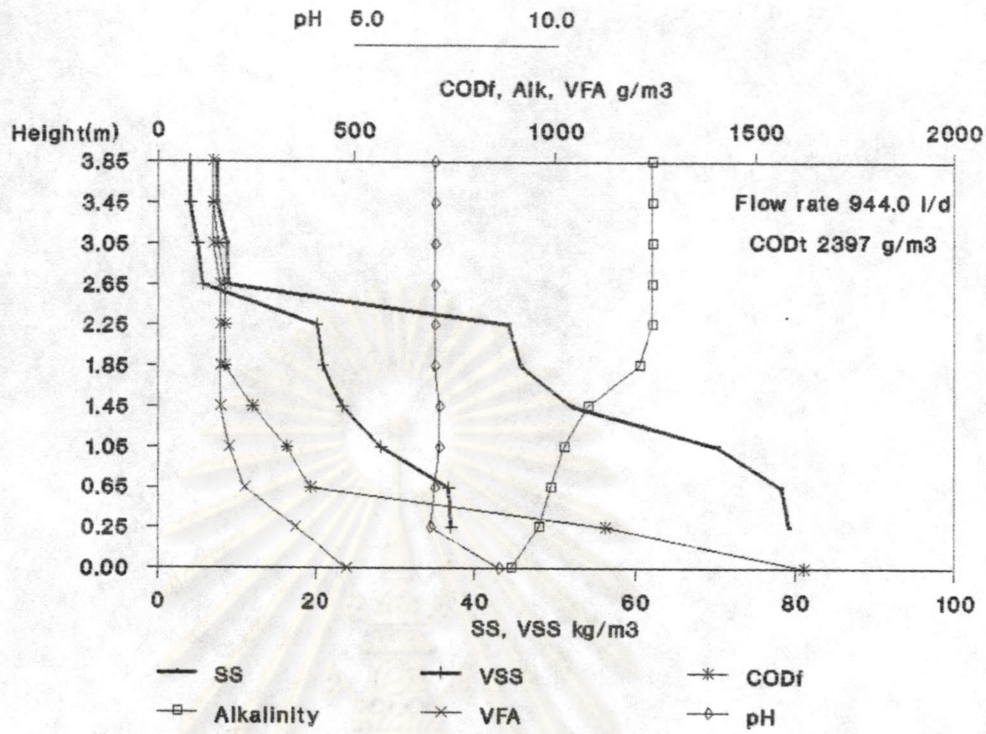


Fig.5.11 UASB profile at HRT 8 hr

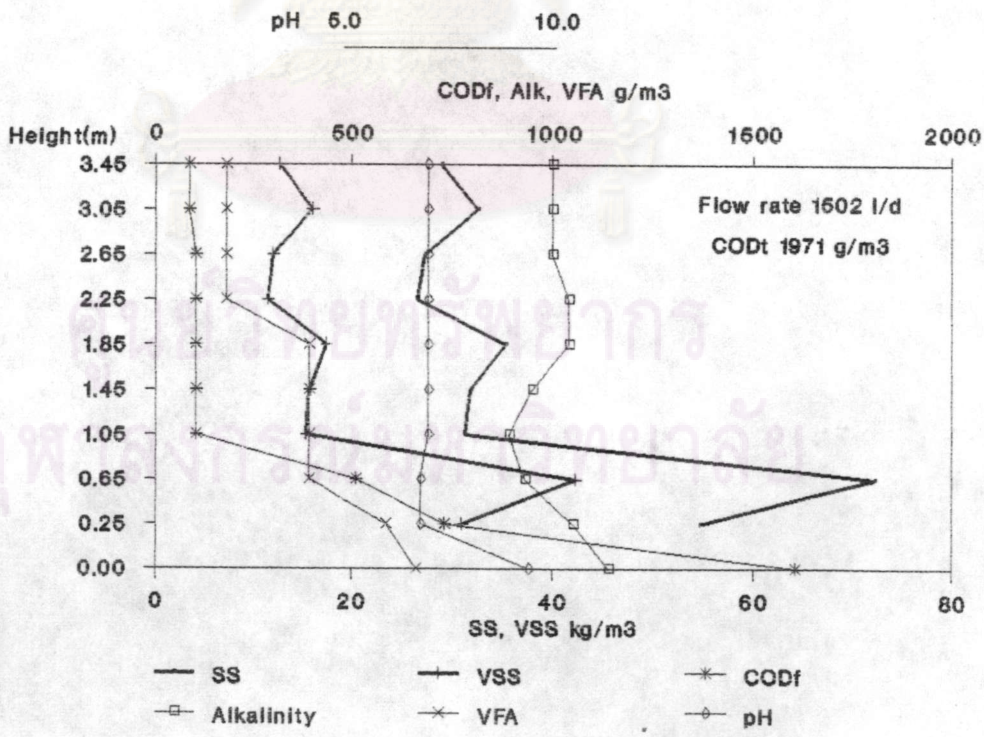


Fig.5.12 UASB profile at HRT 6 hr

Table 5.2

BOD Removal Efficiency vs HRT's

Period (day)	HRT (hr)	Influent BOD (g/m^3)	Effluent BOD (g/m^3)	BOD Removal (%)
9-40	24	1643	47	97.1
52-98	12	1646	85	94.8
123-178	8	1380	49	96.4
209-252	6	1582	52	96.8
263-274	4	1557	61	96.1

It can be seen that the efficiency of BOD removal was in the range of 94 - 97%.

5.2.3 Gas Production

The daily gas production and methane content are illustrated in Figs. 5.15 and 5.16, respectively. The average value of biogas production and its methane content at standard conditions (STP), at various organic loading and HRTs are summarized in Table 5.3 and also illustrated in Figs. 5.17 to 20.

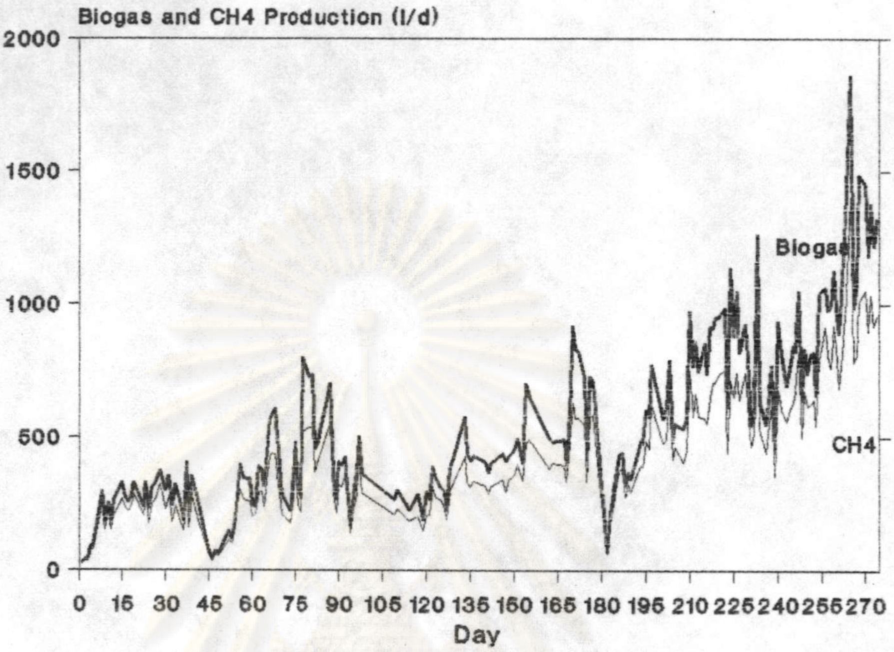


Fig.5.15 Gas and CH4 production

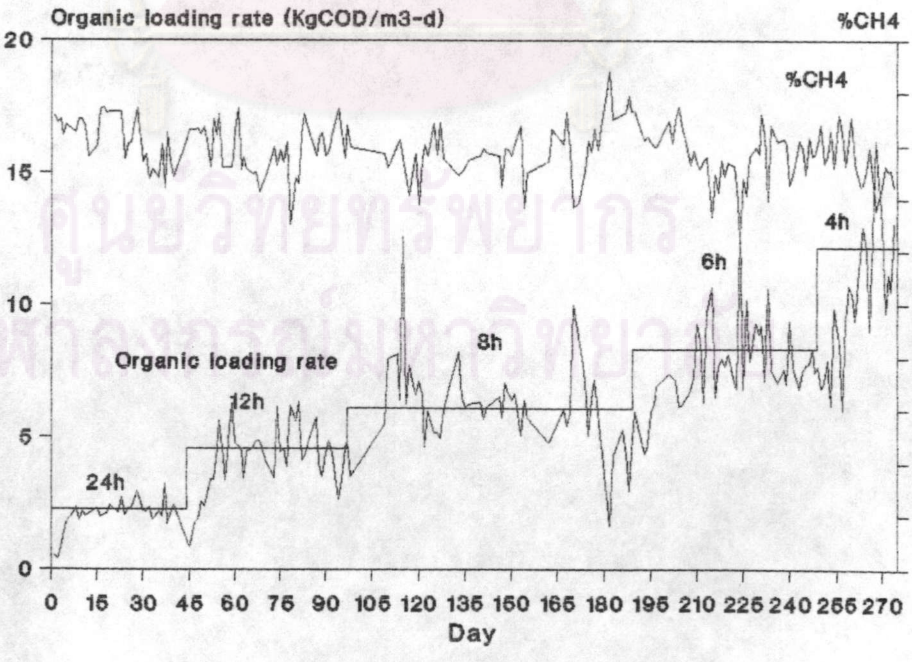


Fig.5.16 Organic loading rate and %CH4

Table 5.3

Biogas Production and CH_4 Content vs HRT's and Organic Loadings.

HRT	Organic Loading Rate	Biogas Production at STP			$\%CH_4$	CH_4 Production at STP		
hr.	(KgCOD/ m^3/d)	l/d	$l/KgCOD_r$	m^3/m^3		l/d	$l/KgCOD_r$	m^3/m^3
24	2.2	254	392	0.81	80.9	205	316	0.65
12	4.5	352	272	0.56	78.8	273	213	0.43
8	6.4	452	243	0.48	77.9	348	188	0.37
6	8.1	728	256	0.49	77.0	556	196	0.37
4	12.4	1204	297	0.54	74.0	890	221	0.40

5.2.3.1 Gas Production with Hydraulic Retention Time (HRT)

The effect of HRT on the biogas production is shown in Fig. 5.17 to Fig. 5.18. It was found that the gas production increased while the hydraulic retention time increased from 4 to 24 hours. The biogas and methane productions per Kg COD removed ranged from 243 to 392 l/KgCOD removed and 188 to 316 l/KgCOD removed, respectively. The gas production per m^3 of wastewater varied in the range of 0.48 - 0.81 m^3biogas/m^3 and 0.37 - 0.65 m^3CH_4/m^3.

5.2.3.2 Gas Production with Organic Loading Rate

The relation between gas production and organic loading rate is shown in Fig. 5.19 to Fig. 5.20. It was found that the gas production is dependent on the organic loading applied.

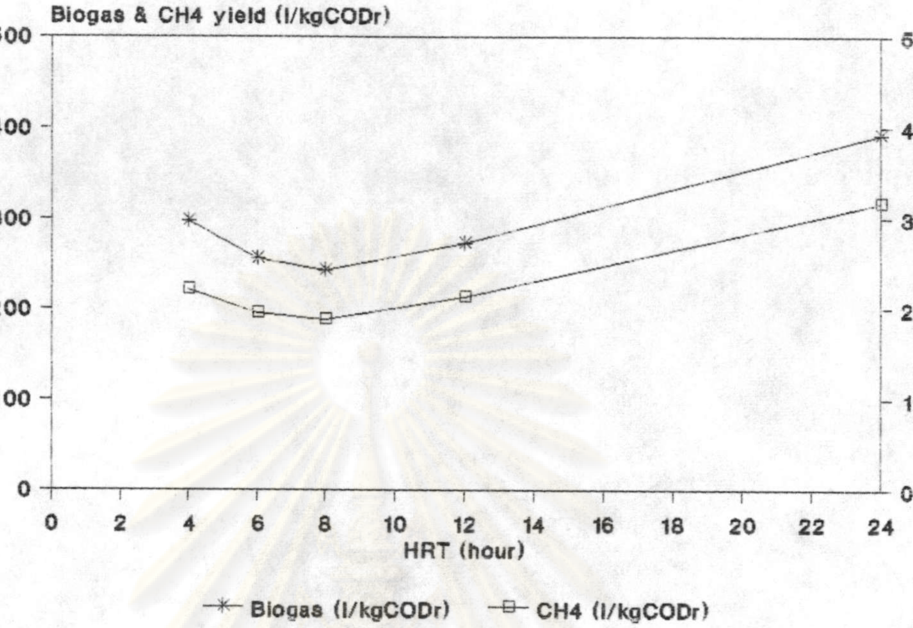


Fig.5.17 Biogas and CH4 production (l/KgCOD) vs HRT

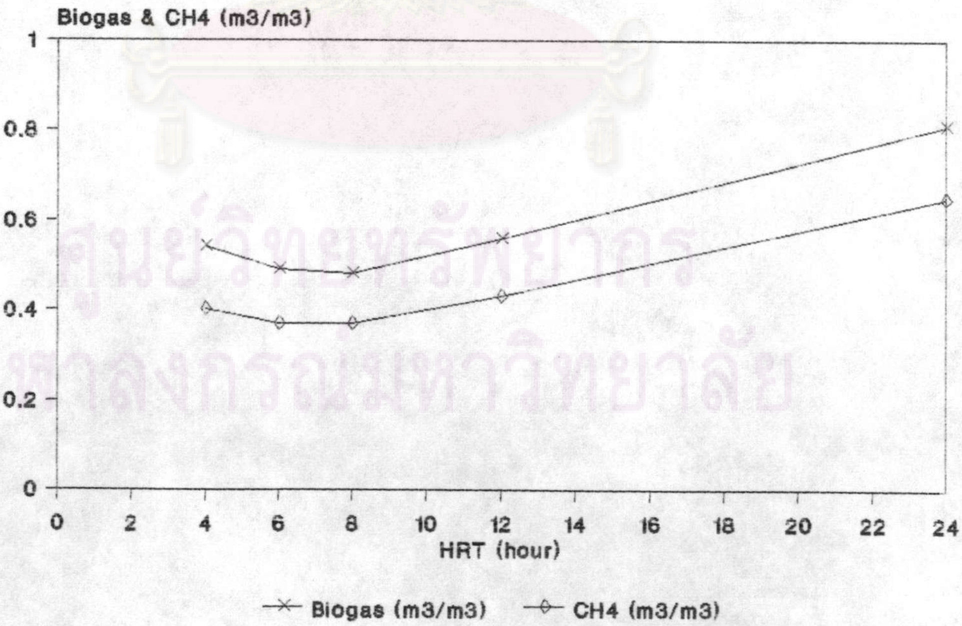


Fig.5.18 Biogas and CH4 production (m3/m3) vs HRT

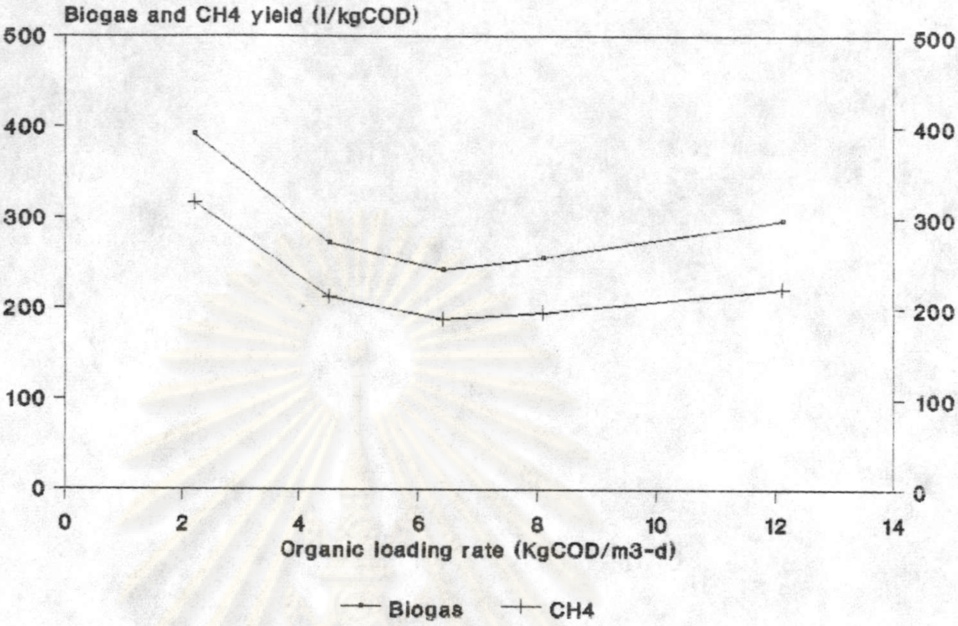


Fig.5.19 Biogas yield and % CH4 vs Organic loading rate
(at constant COD approx. 2000 g/m3)

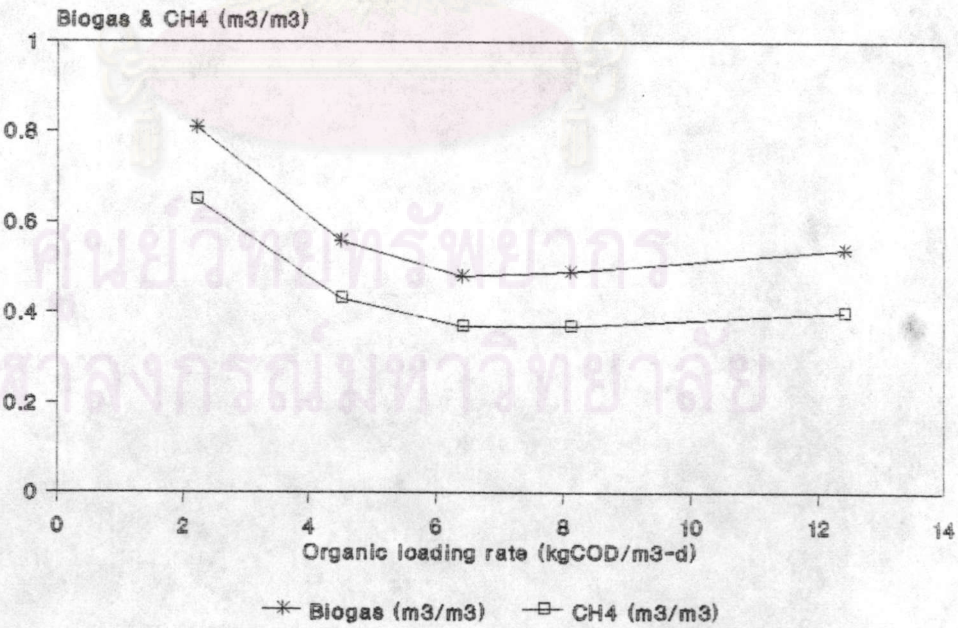


Fig.5.20 Gas and CH4 production (m3/m3) vs organic loading rate
(at constant COD approx. 2000 g/m3)

The gas yield decreased from 392 to 243 l biogas/KgCODr and 316 to 188 l CH_4/KgCODr while the organic loading rate was increased from 2.2 to 12.4 KgCOD/m^3-d. The gas yield varied from 0.48 - 0.81 m^3biogas/m^3 wastewater and 0.37 - 0.65 m^3 CH_4/m^3 wastewater. It should be noted that the CH_4 gas production expressed as l/$KgCOD_r$ (as shown in Table 5.3) increased from 188 to 221 l/$KgCOD_r$ as the organic loading rates increased from 6.4 to 12.4 KgCOD/m^3-d. Despite the fact that methane yield should be decreased with increasing organic loads applied. This increase of the gases might be because there was other gases which could not be measured by the Orsat method i.e., nitrogen (N_2) and/or hydrogen sulfide (H_2S) containing in the biogas produced at higher organic loading rate used.

5.2.4 <u>Gas Composition</u>

The average %CH_4 and %CO_2 by the Orsat method are presented in Table 5.4 and Fig. 5.21 to Fig. 5.22. It can be seen that %CH_4 content increased with HRT and decreased with organic loading, while %CO_2 decreased with HRT and increased with organic loading (Fig. 5.21 and 5.22). The CH_4 content and biogas yield per KgCOD removed decreased with F/M ratio (Fig. 5.23) and increased with sludge retention time (Fig. 5.24). The methane content as high as 80% or more was always obtained while the organic loads applied were lower than 2 KgCOD/m^3-d, particularly below 1 KgCOD/m^3-d. Reasons for high methane content in biogas might be (1) completion of the fermentation and (2) losses of CO_2 in dissolved form in the effluent (as will be discussed further). In general, anaerobic processes treating low strength wastes will always have a high CH_4 content

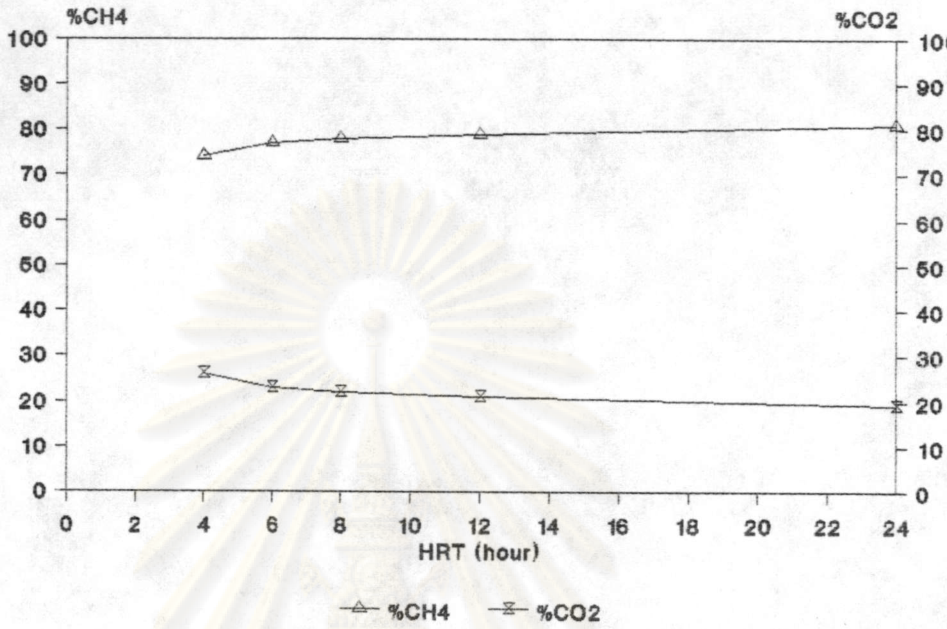


Fig.5.21 CH4 & CO2 content in biogas vs HRT.

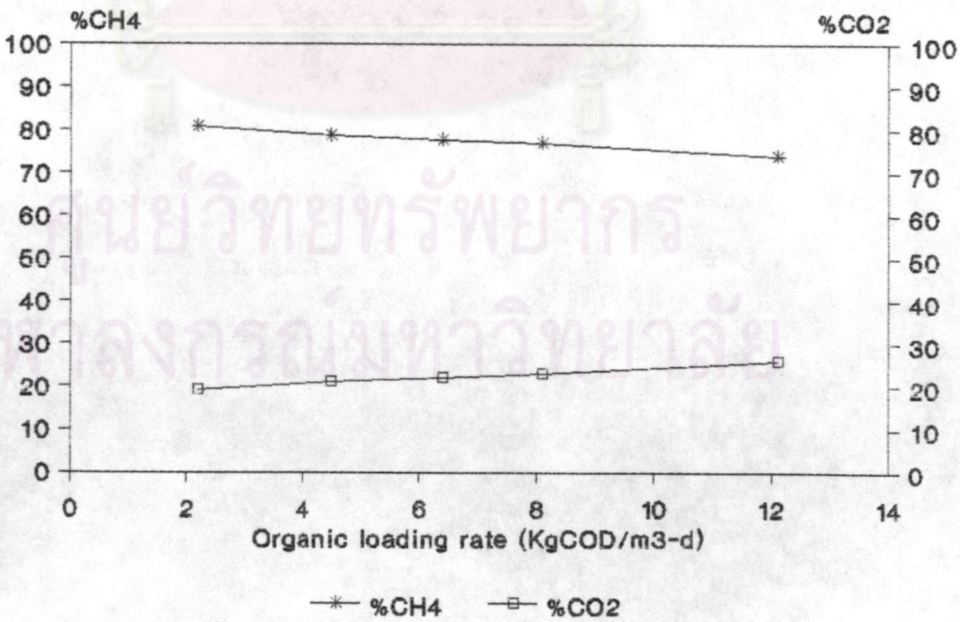


Fig.5.22 CH4 & CO2 content vs organic loading rate.

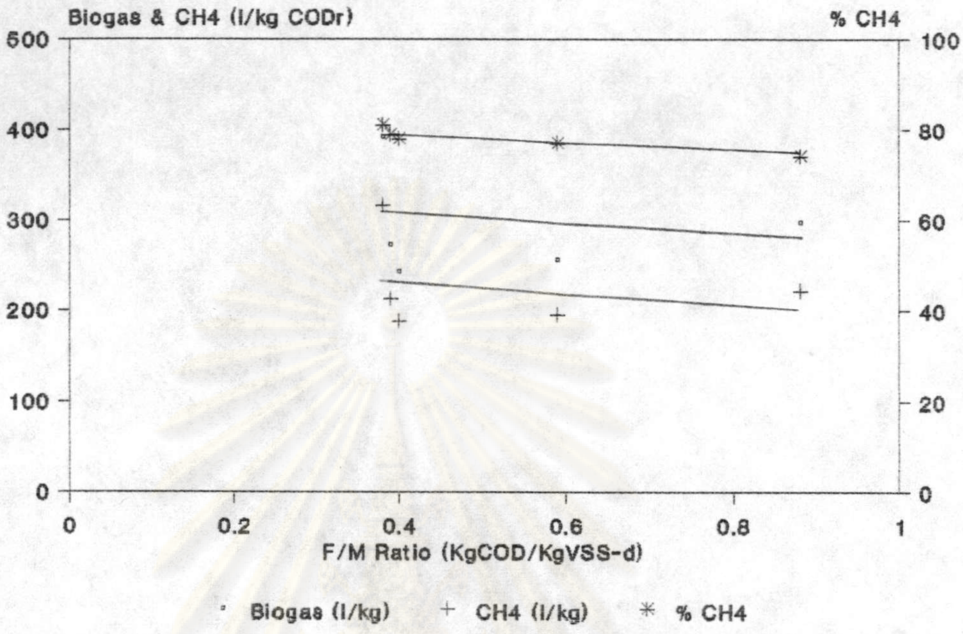


Fig.5.23 Biogas and CH4 production vs F/M ratio.

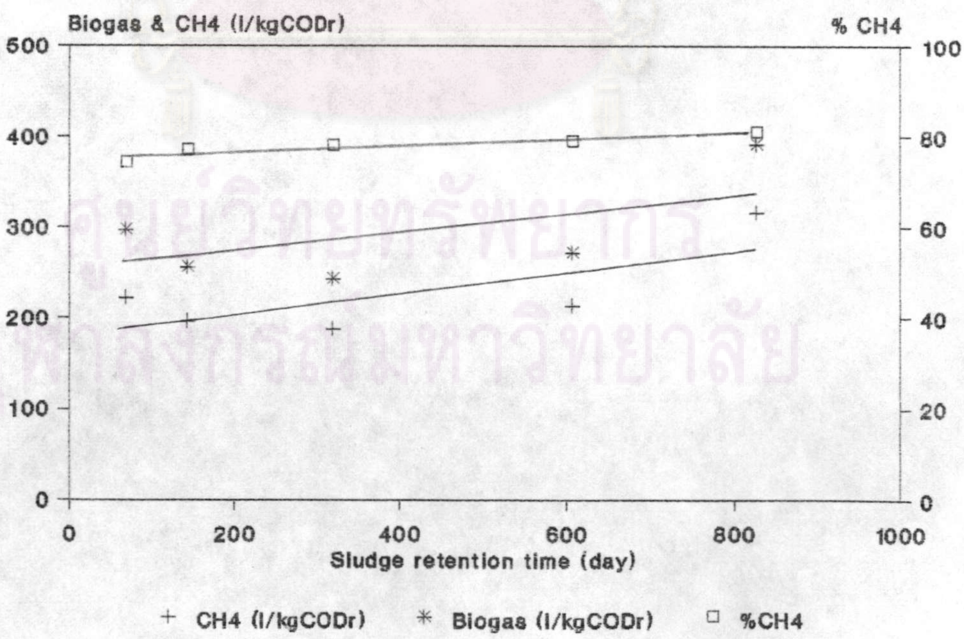


Fig.5.24 Biogas & CH4 production vs sludge retention time.

Table 5.4

The Average CH_4 and CO_2 Content in the Biogas

HRT (hr)	Organic loading rate (KgCOD/m3/d)	$\%CH_4$	$\%CO_2$
24	2.2	80.9	19.1
12	4.5	78.8	21.2
8	6.4	77.9	22.1
6	8.1	77.0	23.0
4	12.4	74.0	26.0

biogas. Similar results were commonly found by Pette (1980), Kobayashi (1983).

5.2.5 Effect of CO_2 Solubility

Biogas production analysed during this experiment shows that the CH_4 content was always high (Table 5.4). This can be explained by the CO_2 solubility based on Henry's law. CO_2 is much more soluble than CH_4, at any constant temperature and normal pressure (as shown in Table 5.5).

Table 5.5

Solubility of CH_4 & CO_2 in Water (ml of Gas Reduced to 0°C and 760 mm Hg, per liter of Water when the Partial Pressure is 760 mm Hg).

Gas	0°	10°	20°	30°	40°
CH_4	55.6	41.8	33.1	27.6	23.7
CO_2	1710	1190	878	665	530

Source : ***Handbook of Chemistry and Physics*, 40th ed., CRC Publishing Co.**

The biogas collected on the top of the UASB reactor was under 15 cm. water pressure (water height in gas meter) and 38°C. The volume fraction of biogas estimated was 23.3 %CO_2, 70.2 %CH_4 and 6.5 % water vapour. The saturated CO_2 concentration estimated was approximately 0.26 g/l which was corresponding to 15 - 25 % of the total biogas produced. At 24 h HRT (hydraulic flow rate equals to 314.5 l/d), approximately 82 g of CO_2 or 42 l is lost in the reactor effluent daily.

5.2.6 Solids Loss from the System

The influent and effluent solids concentration are shown in Fig. 5.25, 5.26 and 5.27. The average solids concentration at various HRT's and organic loading rates, at constant surface overflow rate (SOR) of 1.0 m^3/m^2-h are summarized in Table 5.6.

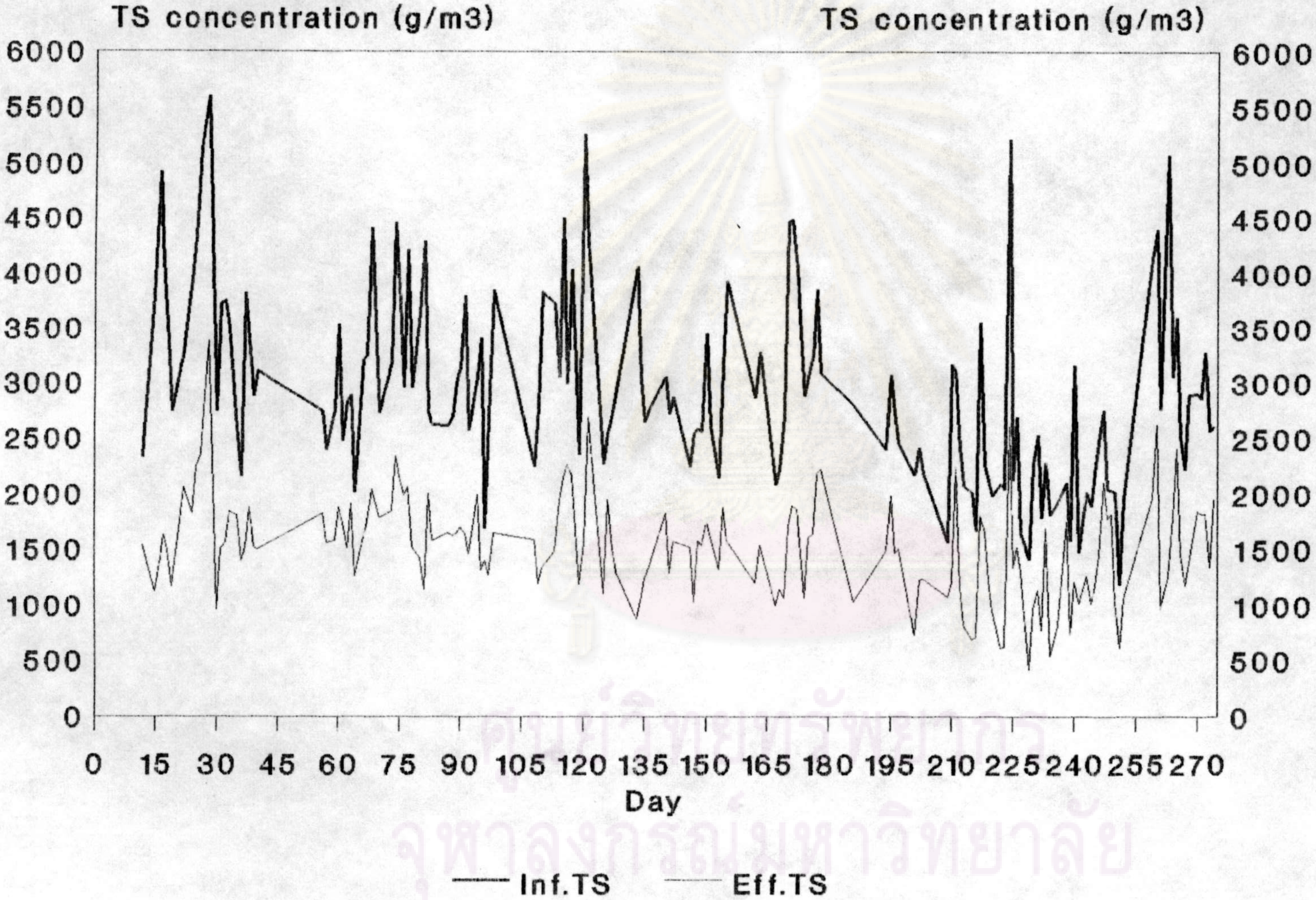


Fig.5.25 Total Solid concentration and efficiency.

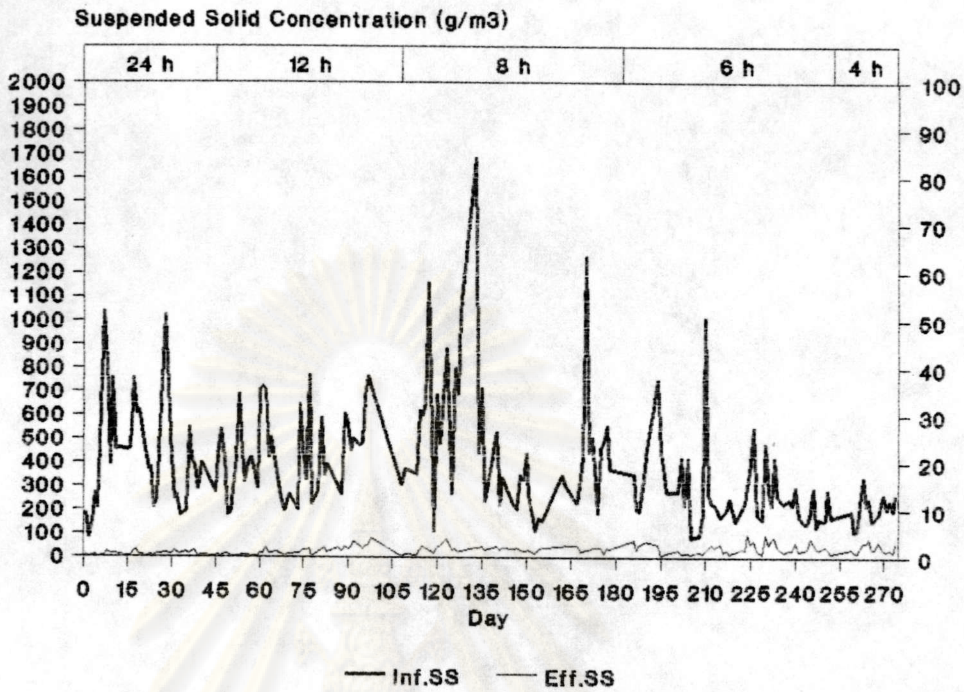


Fig.5.26 Suspended Solid (SS) concentration.

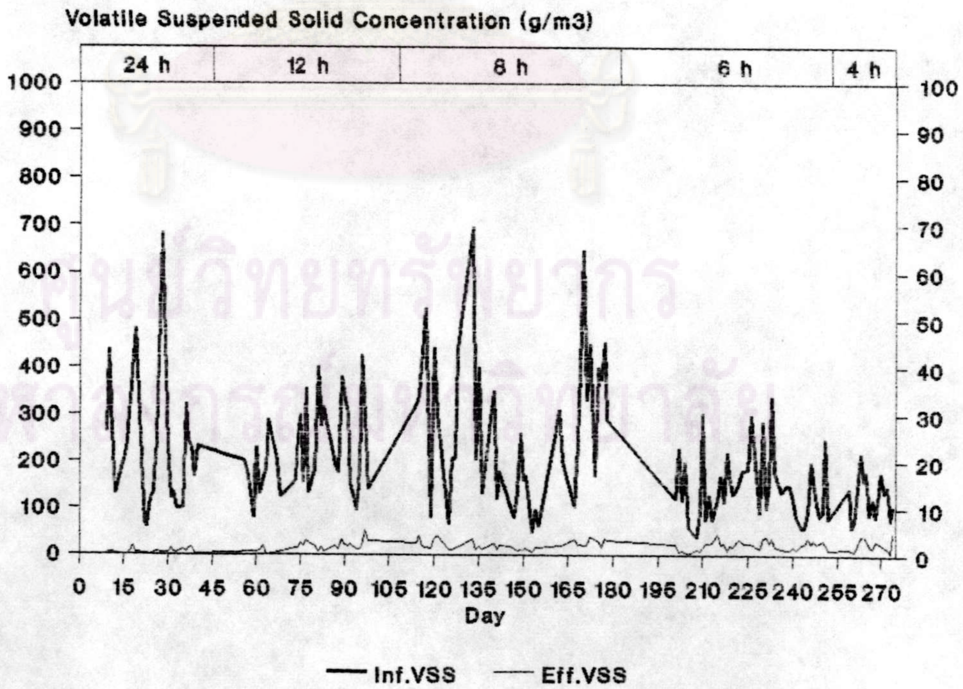


Fig.5.27 Volatile Suspended Solid (VSS) concentration.

It can be seen from Table 5.6 that the variation of total solids in the effluent between 1205 to 1708 g/m^3 while the organic loading rates and the HRT's vary in the range of 2.2 - 12.4 KgCOD/m^3-d and 4 - 24 hrs, respectively. The solids discharged in terms of SS and VSS are affected by organic loading applied and HRT. The solids concentration in the effluent increased with the organic loading and decreased with the HRT's. At higher organic loads (shorter HRT's) higher biogas flow also occurred. This disturbed the flocculation in the settler compartment. By observation, the solids in the effluent usually appeared in black particles which settled down rapidly. The upflow velocity increased with lower HRT. This caused more solids loss from the system, e.g. at HRT's of 6 and 4 hrs the solids loss were 44 gSS/m^3, 24 gVSS/m^3, and 61 gSS/m^3, 28 gVSS/m^3 respectively.

Table 5.6

Solid Loss at Various HRT's and Organic Loading Rates(SOR=1.0 m^3/m^2-h)

HRT (hr)	Organic loading rate (KgCOD/m^3/d)	Influent			Effluent			
		TS (g/m^3)	SS (g/m^3)	VSS (g/m^3)	TS (g/m^3)	SS (g/m^3)	VSS (g/m^3)	VSS (%)
24	2.2	3595	442	237	1708	15	5.8	38.7
12	4.5	3102	462	225	1689	25	17.3	69.2
8	6.4	3001	472	257	1482	36	19.8	55.0
6	8.1	2223	257	150	1205	44	23.7	53.9
4	12.4	3047	226	135	1655	61	27.8	45.6

5.2.7 pH Variation

The influent and effluent pH values are illustrated in Figs. 5.28 - 5.29. The pH profiles in the reactor at HRT's of 24, 12, 8, 6, and 4 h are shown in Figs. 5.9 - 5.13, respectively. The influent pH varied from 6.7 to 10.2. After being filtered by the granular sludge blanket, the pH changed a little in the lower part of the bed and varied slighty in a range of 6.9 to 7.1 in all upper levels of the reactor (as shown in Figs. 5.9 - 5.13). This pH indicated that the reactor performance was normal. Low volatile acids accumulation and high conversion rates were observed (Pohland, 1968).

5.2.8 Alkalinity

The total alkalinity of influent and effluent are shown in Fig. 5.30. The total alkalinity profile in the reactor at HRT's 24, 12, 8, 6, and 4 hours are shown in Figs. 5.9 to 5.13, respectively. The influent alkalinity ranged from 631 to 1082 g/m3 while the effluent alkalinity ranged from 807 to 1010 g/m3, expressed as $CaCO_3$. From Fig. 5.30, it can be seen that the effluent alkalinity is always higher than the influent alkalinity. A wider range of alkalinity present is as a result of the production of ammonia (NH_3) and carbon dioxide (CO_2) during decomposition and their reaction to form bicarbonate alkalinity (NH_4HCO_3) in the reactor.

Each profile in Figs. 5.9 - 5.13 shows that the alkalinity concentration decreased slightly in the lower part of the bed-and then increased in the upper layer.

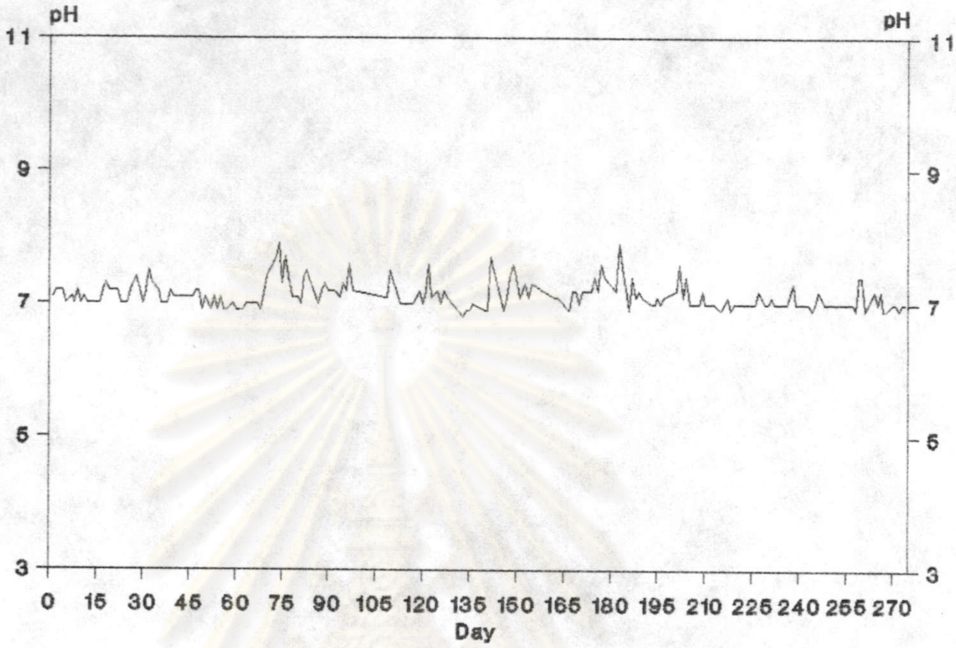


Fig.5.28 pH of effluent.

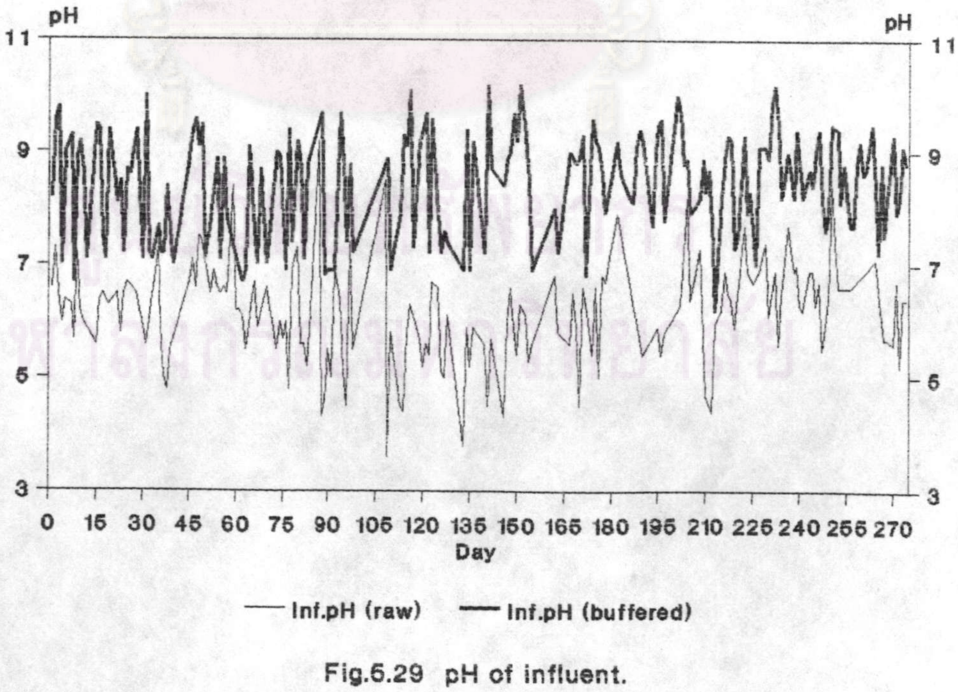


Fig.5.29 pH of influent.

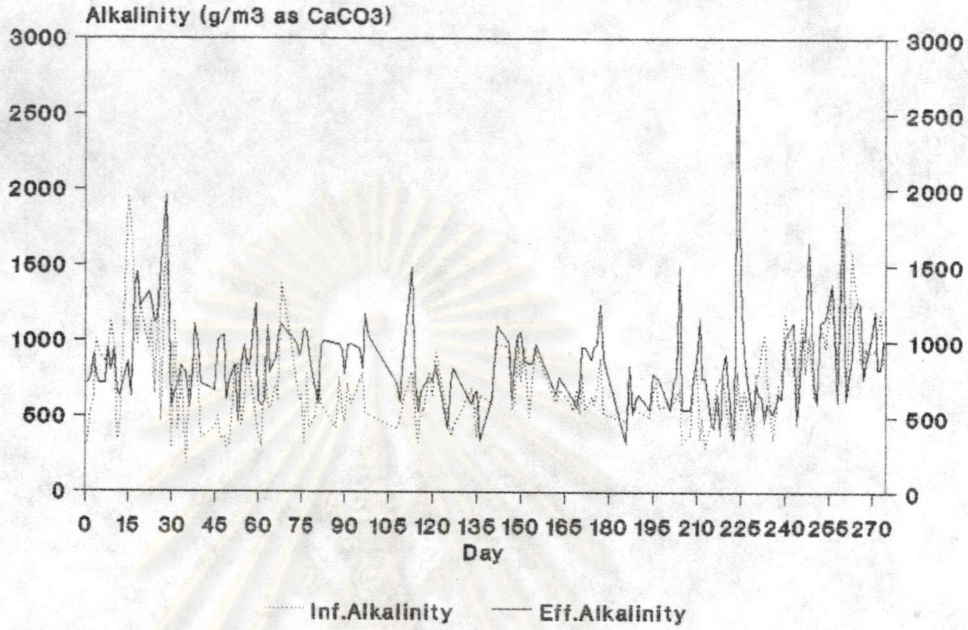


Fig.5.30 Total alkalinity of influent and effluent.

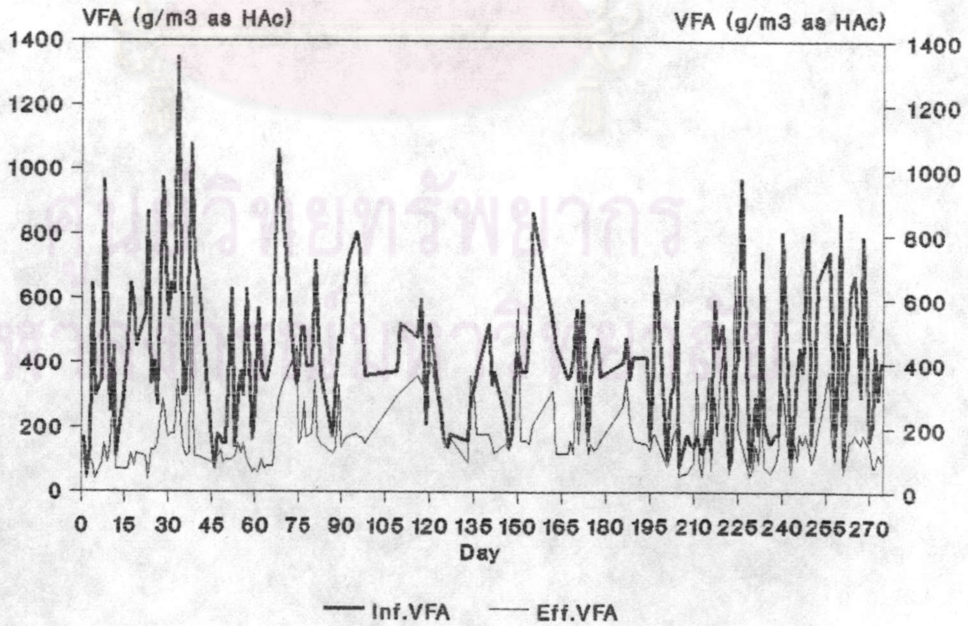


Fig.5.31 Volatile Fatty Acid of influent and effluent.

5.2.9 Volatile Fatty Acid (VFA)

The influent and effluent VFA's are shown in Fig.5.31. The influent VFA varies between 80 to 1350 g/m3, expressed as acetic acid. After being filtered by the sludge blanket, the remaining VFA in the effluent was in the range of 40 to 250 g/m^3 as acetic acid.

The VFA profiles at various heights at HRT's of 24, 12, 8, 6, and 4 hours are shown in Figs. 5.9 to 5.13, respectively. It can be seen that an amount of volatile acid decreases with an increase in height of the reactor. The VFA/Alkalinity ratio of the effluent was in the range of 0.13 - 0.2, which indicates normal reactor operation (WPCF's manual of practice No. 16). It should be noted that the brewery wastewater used underwent rapid hydrolysis and acidogenesis when stored in a holding tank, particularly at longer HRT's feeding. By observation during the period of 24 h HRT, the VFA content increased to 1000 g/m^3 as HAc. or more and accompanied by a pH drop below 6.6 within 4 to 6 hours.

5.2.10 TKN and TP Removal

The total phosphate and the total kjadahel nitrogen in the influent and the effluent are shown in Fig. 5.32 and Fig. 5.33, respectively. Approximately 20% - 30% of the TPO_4^{3-} was eliminated. The TKN removal was about 50%. The main reason for the elimination is that, apart from being used for cell growth , some part of TKN might leave the system as NH_3 gas. (Sawyer & McCarty, 1978).

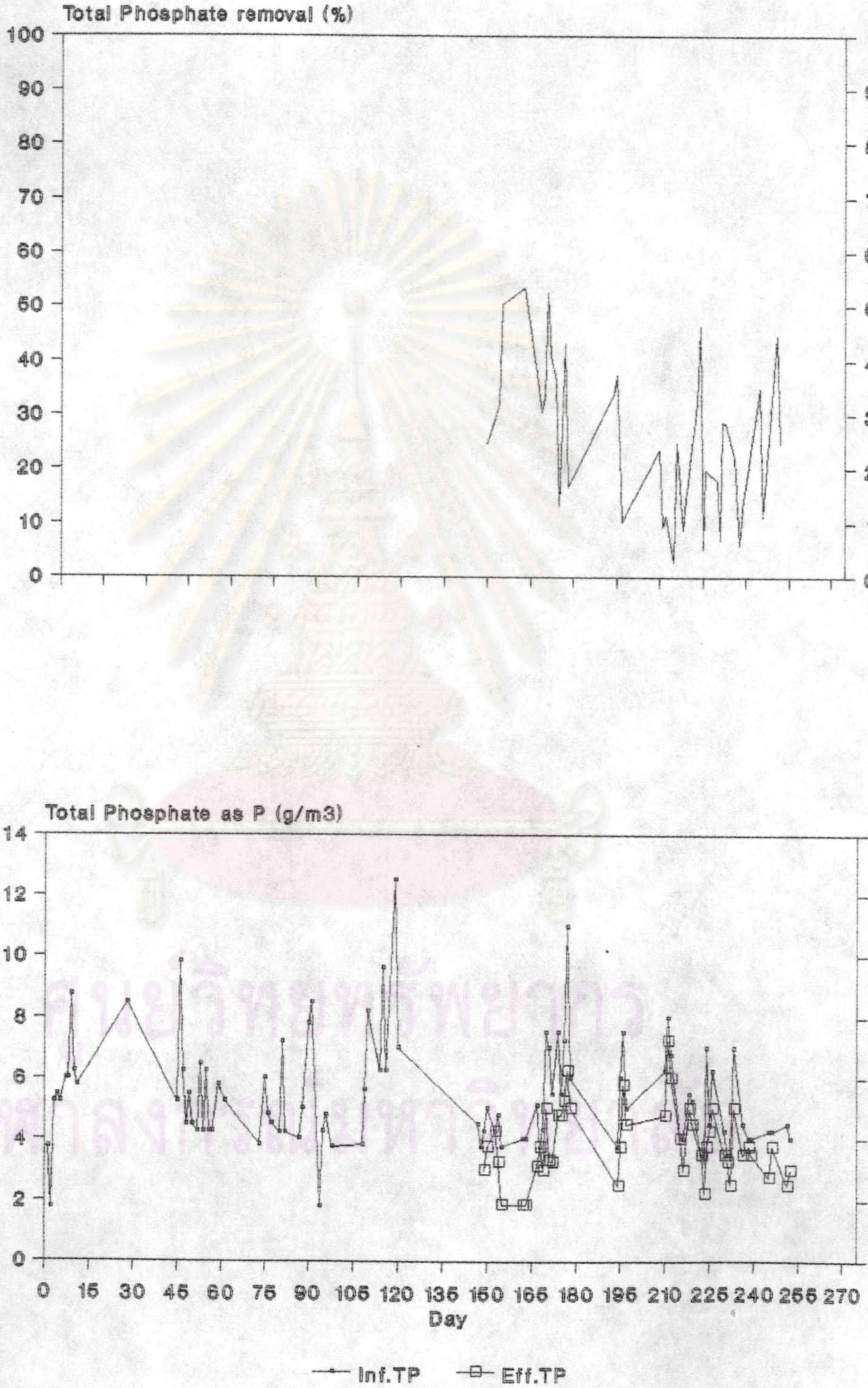


Fig.5.32 Total Phosphate of influent & effluent and efficiency

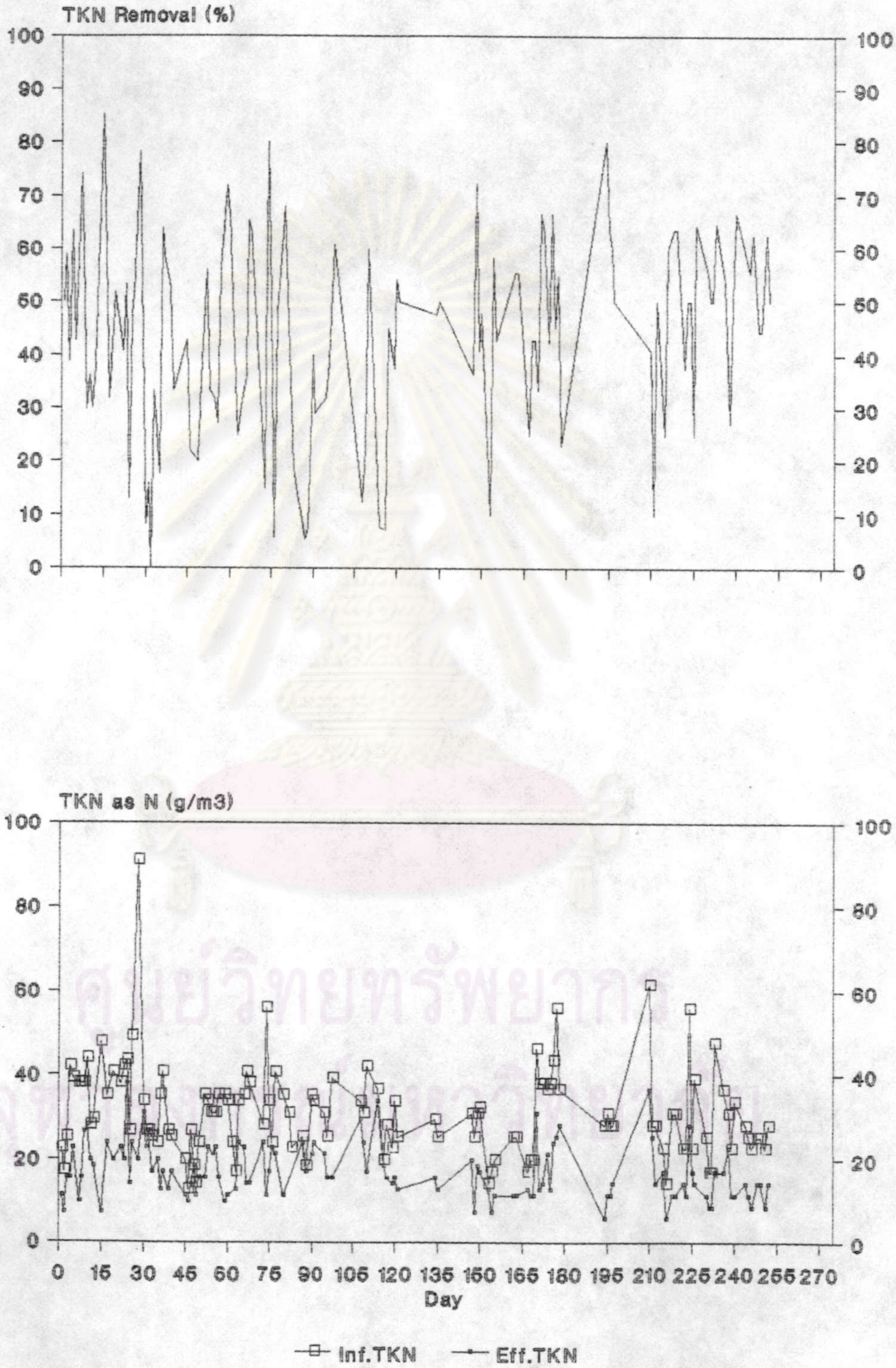


Fig.5.33 TKN of influent & effluent and efficiency.

5.3 Sludge Development and Characteristic

The total amount of sludge developed in the reactor, during the 310 days of operation since the start-up time is shown in Table 5.7 and illustrated in Fig. 5.3. This duration did not include the feedless period for maintenance and/or repair of pumps which took about 2 - 3 weeks between the run. From Fig. 5.3, it can be seen that the amount of sludge (TSS) increased continuously until the end of 8 h HRT's experiment, and then gradually decreased after reaching the period of 4-6 h HRT's operation. This is due to that there may be much solid in SS form loss in the effluent during the shorter HRT's investigation, because of the high upflow rate of wastewater applied to the reactor.

Regarding the sludge blanket behavior, it is shown as SS and VSS profile at various heights in the different days of operation in Fig. 5.34. It can be seen that the shape of any profile depends strongly on the pattern of hydraulic and organic loading rate applied. Due to the reason either the selective pressure or plug-flow type, the sludge granules were rapidly developed in the bottom, characterized by a sludge bed with a concentration of about 30 to 80 $KgSS/m^3$ and 15 to 40 $KgVSS/m^3$. Meanwhile the sludge particles/flocs with concentration of about 5 to 25 $KgSS/m^3$ and 2 to 15 $KgVSS/m^3$ was suspended in the upper layer. The concentrated zone of sludge bed was usually found to a depth of about 1.5 - 2 m in the reactor.

At HRT's of 24 to 8 hrs the densed sludge occupied the lower part of the reactor while the floculant sludge blanket occupied. The upper part and the profile was stable. At HRT of less than 8 hrs, a

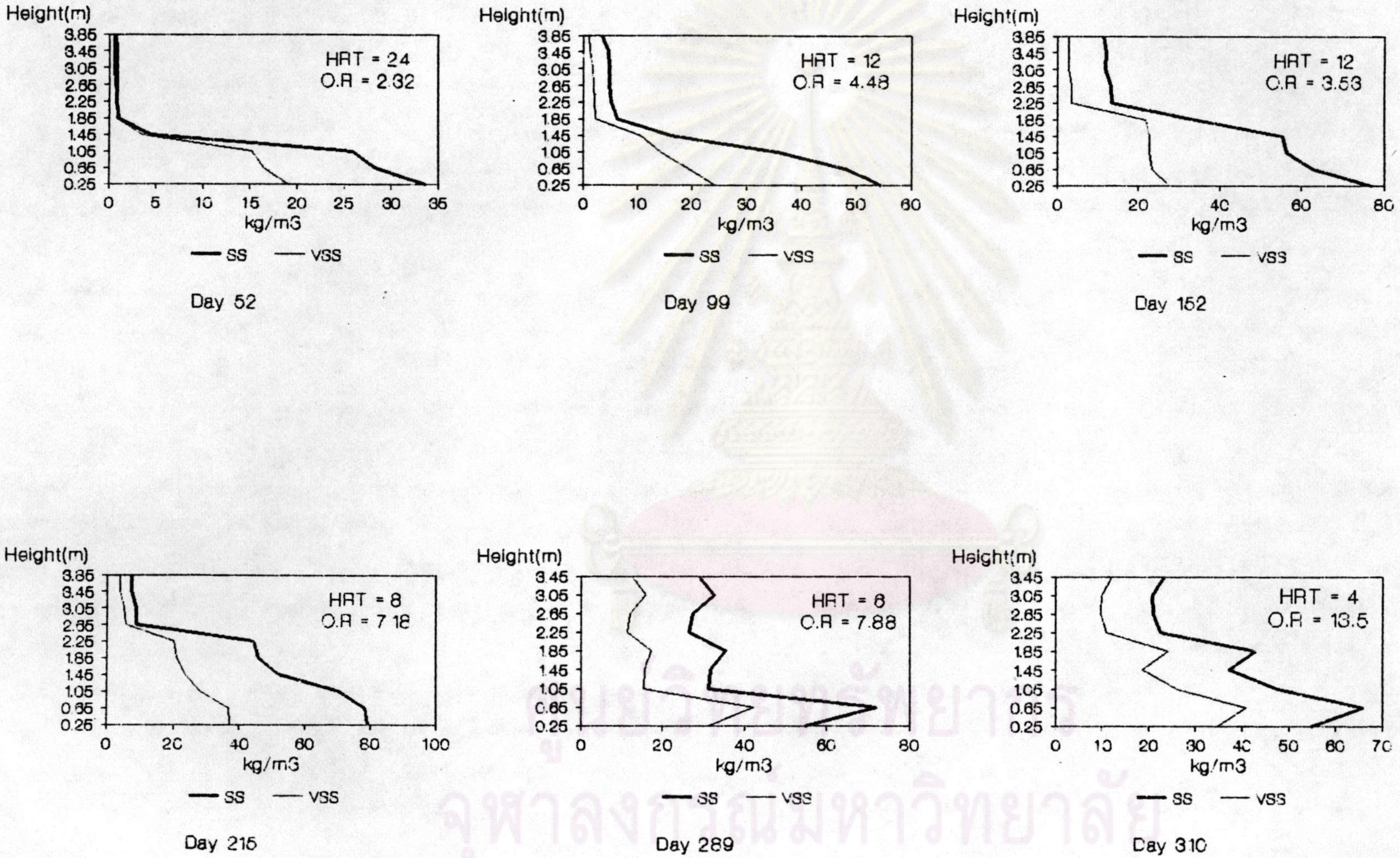


Fig. 5.34 Some sludge profile in UASB pilot-plant at day 52, 99, 152, 215, 289 and 310.

lager part of the sludge bed was lifted upward. This is mainly as a result of the marked turbulence brought about by rising gas bubbles, as well as the increasing tendency of the granules to float (quoted by Lettinga *et al.,* 1984). However, the process could still perform well and showed no sign of failure.

Table 5.7

Sludge concentration measurement made over the whole experimental time.

Day	TSS (g)	avg. TSS (Kg/m^3)	TVSS (g)	avg. TVSS (Kg/m^3)
1	4980	17.8	2441	8.7
24	4614	16.5	2317	8.3
35	5007	17.9	2342	8.4
86	4613	16.5	2128	7.6
99	4977	17.8	2318	8.4
115	5806	17.9	2343	8.4
135	9538	34.2	3655	13.1
215	10888	43.4	5002	19.9
284	9321	37.2	5102	20.3
289	9426	37.6	5133	20.5
310	9318	37.1	5151	20.5

5.4 Effect of Reactor Height

The various parameters i.e., COD, VFA, alkalinity and pH at various reactor heights are found in similar pattern in all operation of HRT's 4 to 24 hrs (see Fig. 5.9 - 5.13). It can be seen that almost all of the COD concentration is eliminated within the lower portion 1.5 m height from the bottom of the reactor in accordance with the rapid degrading of the volatile acid whose concentration is never beyond the neutralizing ability of the buffer present in the same zone. This is accompanied by the neutral pH range from 6.9 to 7.1 throughout the upper portion of the reactor. In addition, a further change in any of these factors is not observed over the height of 1.5 - 2 m. This satisfactory performance of the UASB reactor is achieved from the effective work in harmony between two groups of acid former and methane former bacteria in such a way that they can ferment anaerobically the organic waste to form methane and carbon dioxide. The majority of waste conversion rate was found to occur in the first zone about 65 cm from the bottom which also had the highest granular sludge concentration. Therefore, the increasing volume can be done by an increase in the cross-section of the reactor and not by an increase in height.

5.5 Effect of Feedless Condition

After the feedless period of 2-3 weeks, a very interesting feature for this operation was notable. It was observed that the system could be restarted-up within a few hours after resuming the feed substrate. Fig. 5.35 show the relationship between the restart up time and the gas production, at the beginning of 6 and 4 h HRT's experiment. It can be seen that the system takes approximately 2-3 hours before the gas production reaches the maximum level.

A very short time required for the restart up procedure was partly dependent on the temperature. The temperature of the sludge

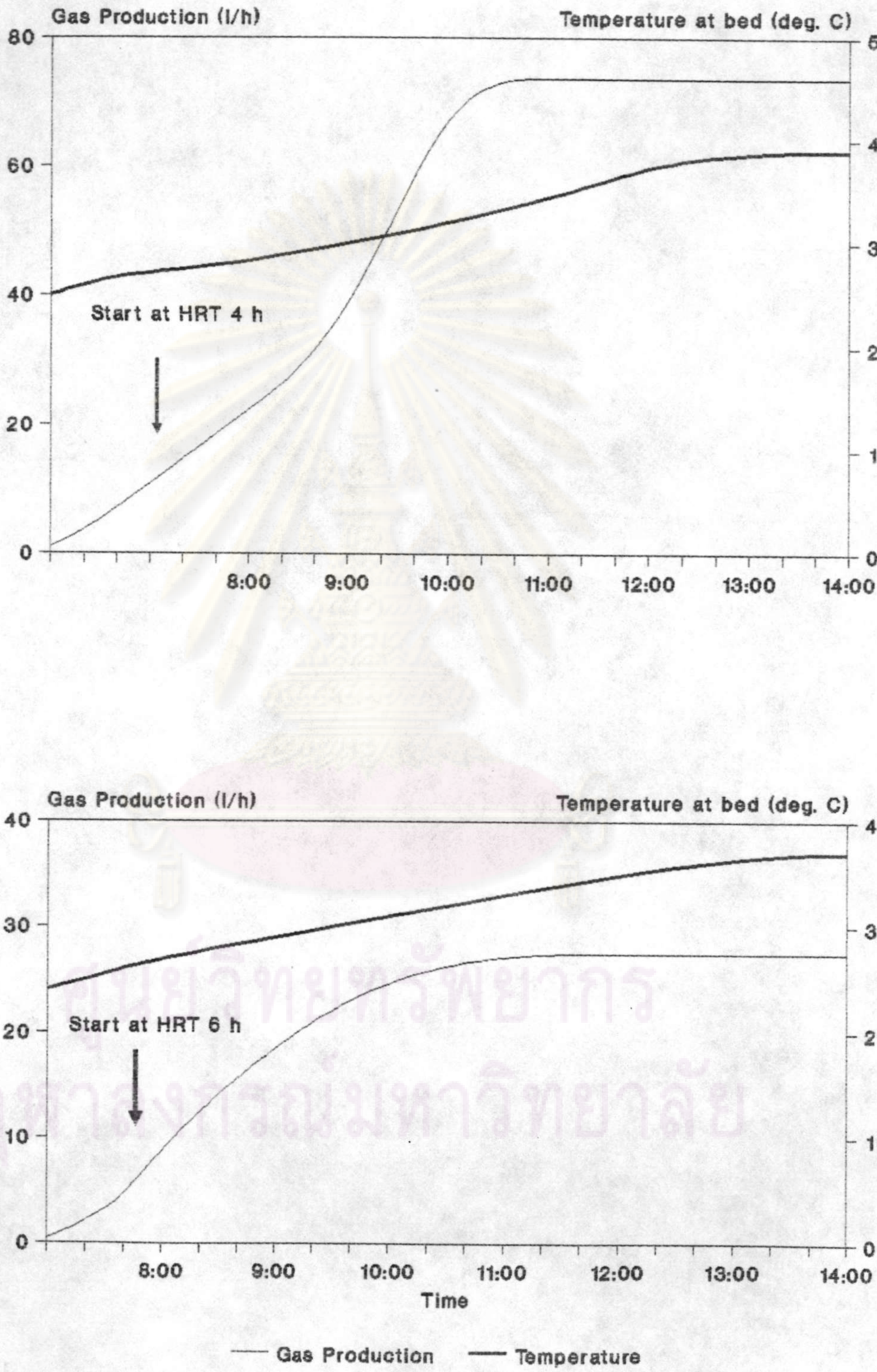


Fig.5.35 Gas production rate during restart up after operation shutdown

bed is increased from 25° - 39°C during the restart up time. The same pattern was observed in the 800-m^3 UASB plant experiment treating maize starch wastewater at T 30° - 40°C, during the weekend shutdown (Zeevalkink and Maahkant, 1984).