CHAPTER V

RESULTS AND DISCUSSION

This chapter will be focused on the experimental results and the discussion of parameters which affect the permeation performance of microfiltration both with and without ultrasound. Effect of ultrasonic irradiation on the membrane and the yeast will also be described. In the last section, the economic analysis of ultrasonic system will be discussed.

5.1 Effect of the applied pressure on permeation performance

The study of the effect of applied pressure on permeation performance took place over 5 transmembrane pressures; 11.27, 16.66, 26.46, 36.26 and 46.06 kPa. A permeate flux, which was calculated by dividing the permeate flow rate with filtration area (223.2 cm^2), was a criteria to show the performance of the microfiltration.

The permeate flux was proportional to the transmembrane pressure while demineralized water was filtered through a ceramic membrane as shown in Figure 5-1.

When yeast suspension was filtered without ultrasound, it is found that the permeate flux was initially increased with increasing applied pressure and reach the maximum value at the pressure of 26.46 kPa. Higher increasing pressure above this point effected the less steady-state permeate flux. This finding follows from the fact that a gel layer was formed over the filtration areas and acted as gel resistance which would diminish the permeate flux as described in section 3.1.2. Although the permeate flux is proportional to the applied pressure, it is found that increasing pressure will also result

in more compaction of gel layer and this makes permeate flux reach a certain maximum point and is independent of the further applied pressure [5].

In the case that ultrasound was applied, it was obviously obtained that permeate fluxes were increased in the ratio of 1.6 to 2.8 as against filtration taken without ultrasound at the same conditions. Cavitational collapse induced by ultrasound would eliminate cake layer over the membrane surface as illustrated in the less of cake layer resistance (R_c) in the ratio of 3 to 6 comparing to those observed in filtration without ultrasound as shown in Table 5-2. In addition, ultrasound also slightly reduced the plugging resistance (R_p).

Initial increasing pressure expressed the increase in permeate flux, and this can be explained as previously mentioned in case of filtration without the sound irradiation. The maximum permeate flux was observed at the pressure of 26.46 kPa. Further increasing pressure resulted in the less permeate flux. As the higher pressure was introduced, the thicker gel accumulated and this made the permeate flux reach the certain maximum value, and then became relatively constant with further applied pressure. A consideration of Equation (3-17) shows that in the presence of acoustic field, the bubble will grow when $P_v + P_g > P_h - P_a + (2\sigma/R_0)$. Thus, the increase of external pressure (P_h) to the liquid medium would lead to the increase of the cavitation threshold, thereby resulting in the less cleaning capability.

In conclusion, the applied pressure would help increasing in permeate flux in the initial region that the compaction of cake layer was not strong. Moreover, there was limitation in flux increasing capability influenced by the cavitation effects which observed to be the same point at 26.46 kPa in both filtration with and without ultrasound, and hence was selected for the further studies.

Table 5-1: Steady-state permeate fluxes at various applied pressures

applied pressure (kPa)	permeate flux, off ($cm^3/cm^2.s$)	permeate flux, on ($cm^3/cm^2.s$)	increased flux (times)
11.27	0.00065	0.00187	2.9
16.66	0.00069	0.00194	2.8
26.46	0.00084	0.00202	2.4
36.26	0.00077	0.00127	1.7
46.06	0.00075	0.00123	1.6

Table 5-2: Comparison of various resistance in filtration with and without ultrasound

ΔP_{TM}	ultrasonic off				ultrasonic on			
(kPa)	R_m	R_c	R_p	R_t	R_m	R_c	R_p	R_t
11.27	8.04	178.39	11.46	197.89	8.04	36.30	8.70	53.04
16.66	5.76	243.83	11.74	261.33	5.76	41.37	7.31	54.44
26.46	6.98	317.58	21.32	345.88	6.98	108.95	13.77	129.70
36.26	8.89	523.04	29.20	561.13	8.89	181.56	23.92	214.37
46.06	10.03	663.29	39.68	713.00	10.03	220.44	35.31	265.60

Conditions: u = 0.29 m/s, P = 25 W, C_b = 0.005 g/cm^3

Unit of resistance: $x10^6$ (1/cm)

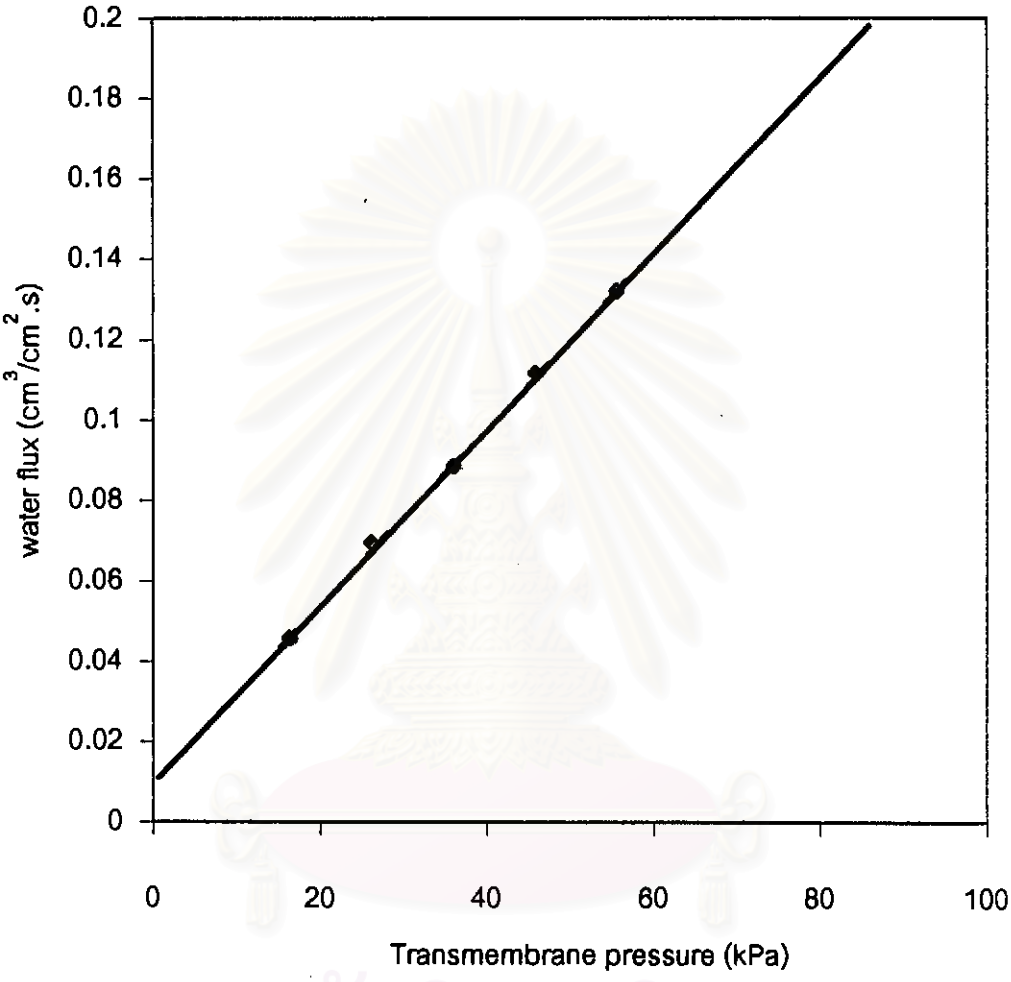


Figure 5-1: The effect of applied pressure on permeate flux of demineralized water

- Operating temperature of 30℃
- Feed flow velocity of 0.48 m/s

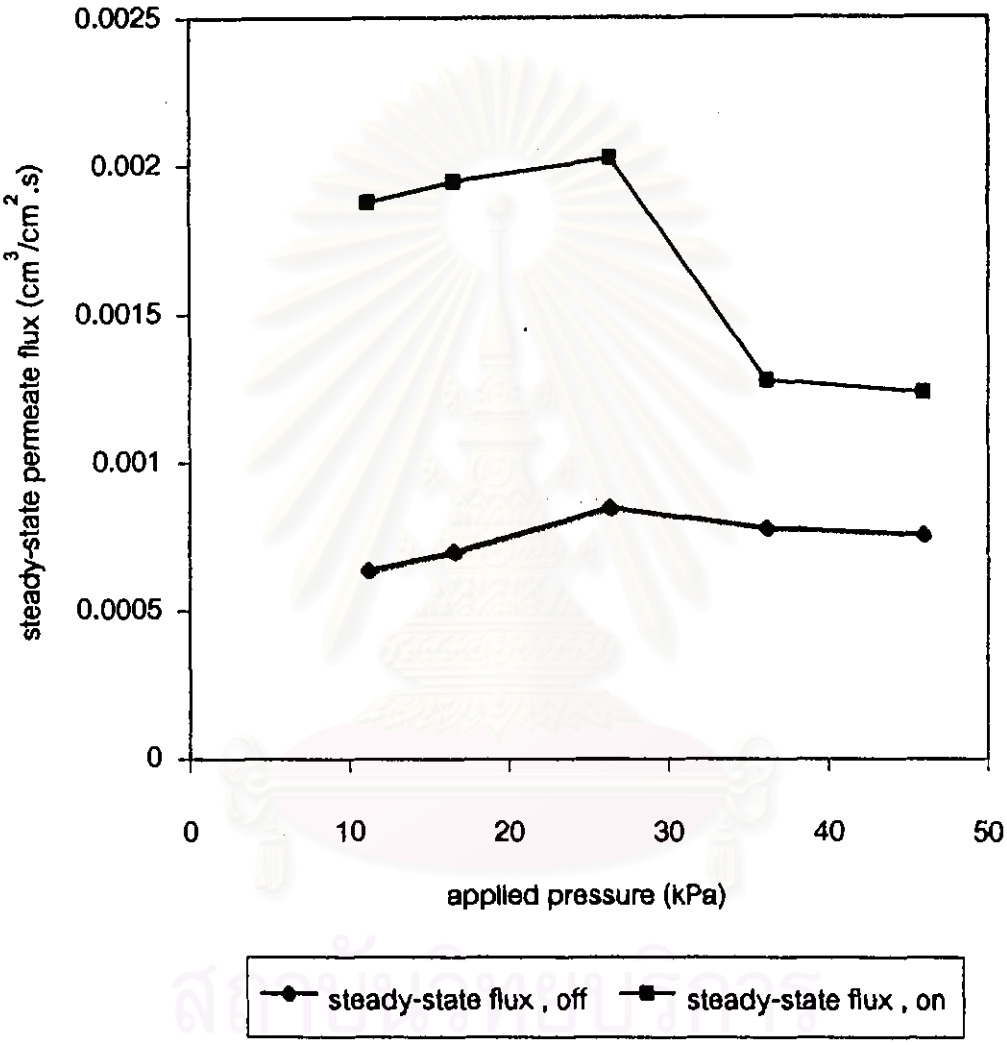


Figure 5-2: The effect of applied pressure on permeate flux of yeast suspension

- Operating temperature of 30℃
- Feed flow velocity of 0.29 m/s
- Feed concentration of 0.005 g/cm^3

5.2 Effect of the feed flow velocity on permeation performance

Under the applied pressure of 16.66 kPa and the feed concentration of 0.005 g/cm^3, a set of experiment was taken on studying the effect of four feed flow velocities (0.02, 0.17, 0.29 and 0.48 m/s) on the permeate flux of microfiltration with and without ultrasound.

The permeate flux increased with the feed flow velocity in case that ultrasound was not applied to the filtration as shown in Figure 5-3. This is because of the increasing in feed flow velocity enhanced the shear force at the membrane surface, hence the thickness of cake formation over the membrane surface decreased with increased feed flow velocity. This obviously expressed in the less cake resistance (R_c) in the ratio of 1 to 2 with increasing feed flow velocity as illustrated in Table 5-3.

In case of microfiltration coupling with ultrasonic irradiation, the higher permeate flux in the ratio of 1.7 to 3 was detected in comparison with those observed in the filtration without ultrasound. This is because the cake layer was removed by ultrasonic cleaning and continually swept away from the membrane surface by the feed flow. However, the rate of flux increasing was decreased when higher feed flow velocity was introduced. Considering the decrease of cake resistance (R_c) by ultrasonic irradiation (See Table 5-4), it is found that the higher feed flow, the less reduction of cake resistance. This can be explained that at a very high feed flow velocity, the cake layer was mainly removed by high shear generated so that the ultrasonic effect on cake removal was lessened when compared to those observed at the lower feed flow velocities. In addition, the performance of the microimpact destruction might be decreased as a result of the high turbulent disturbance occurred with the application of high feed flow velocity.

In conclusion, the permeate flux of microfiltration coupling with ultrasonic irradiation expressed the maximum certain point at the feed flow velocity of 0.29 m/s, and hence was selected for further studies.

Table 5-3: Steady-state permeate fluxes at various feed flow velocities

feed flow velocity (m/s)	permeate flux, off ($cm^3/cm^2.s$)	permeate flux, on ($cm^3/cm^2.s$)	increased flux (times)
0.02	0.0005	0.0015	3.0
0.17	0.0006	0.0018	3.0
0.29	0.0007	0.0019	2.7
0.48	0.0010	0.0019	1.9

Table 5-4: Comparison of various resistance in filtration with and without ultrasound

u	ultrasonic off				ultrasonic on			
(m/s)	R_m	R_c	R_p	R_t	R_m	R_c	R_p	R_t
0.02	4.36	156.16	17.60	178.12	4.36	67.26	6.78	78.40
0.17	4.36	144.31	14.66	163.33	4.36	57.33	5.90	67.59
0.29	4.36	97.50	13.14	115.00	4.36	44.59	5.49	54.44
0.48	4.36	71.51	22.13	98.00	4.36	44.49	5.59	50.08

Conditions: ΔP_{TM} = 16.66 kPa, P = 25 W, C_b = 0.005 g/cm^3

Unit of resistance: x10^6 (1/cm)

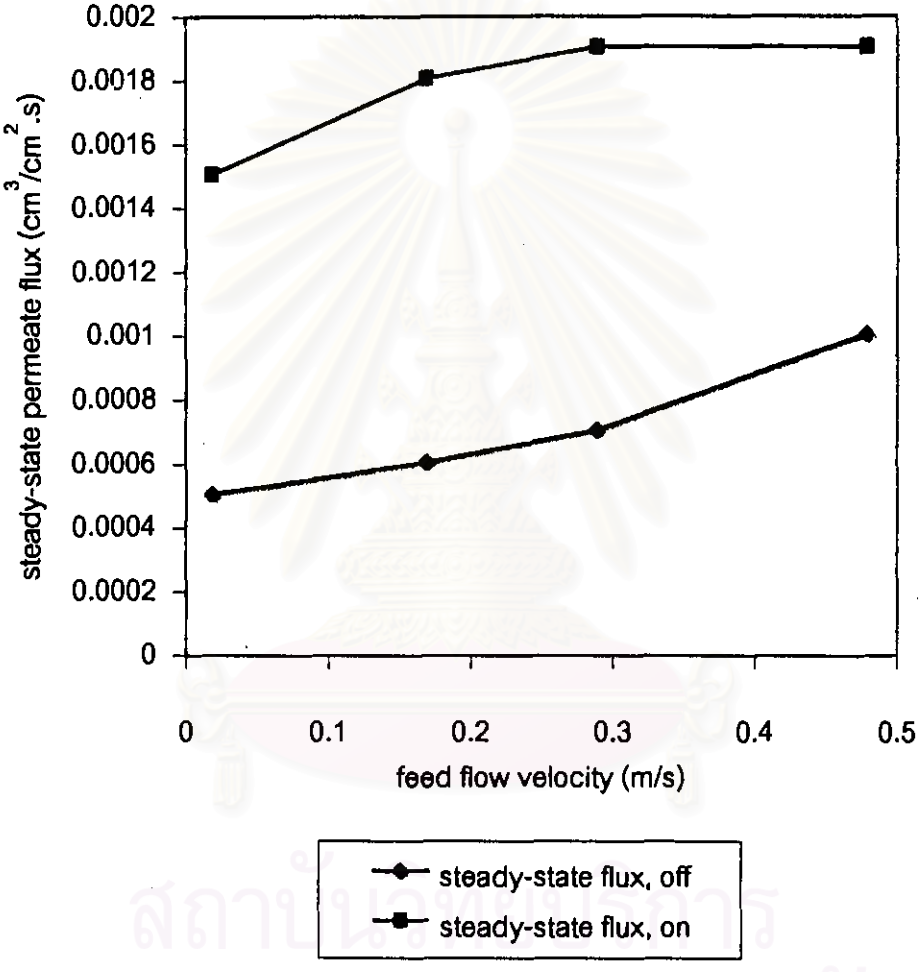


Figure 5-3: Permeate flux of yeast suspension as a function of feed flow velocity

- Operating temperature of 30℃
- Applied pressure of 16.66 kPa
- Feed concentration of 0.005 g/cm^3

5.3 Effect of the feed concentration on permeation performance

The feed concentrations of 0.005, 0.010 and 0.020 g/cm^3 were varied to examine their effects on permeation performance of microfiltration with and without sound field.

Without ultrasound, the higher feed concentration was introduced, the less permeate flux was observed as shown in Figure 5-4. This was resulted from the thick cake layer increased with increasing cell concentration [11]. When ultrasound was applied to the filtration, the higher permeate flux in the ratio of 1.9 to 2.4 due to the cake removal induced by cavitation bubbles was detected. It is also found that permeate flux was decreased with the higher concentration introduced. In addition, it is expressed that ultrasonic effect on the increasing permeate flux was not diminished with the higher concentration introduced. Since ultrasound was transferred through the permeate channel, there was no attenuation due to wave scattering and absorption with particles.

Table 5-5: Steady-state permeate flux at various feed concentration

feed concentration (g/cm^3)	permeate flux, off (cm^3/cm^2.s)	permeate flux, on (cm^3/cm^2.s)	increased flux (times)
0.005	0.00086	0.00172	2.0
0.010	0.00065	0.00123	1.9
0.020	0.00034	0.00080	2.4

Table 5-6: Comparison of various resistance in filtration with and without ultrasound

C_b	ultrasonic off				ultrasonic on			
(g/cm^3)	R_m	R_c	R_p	R_t	R_m	R_c	R_p	R_t
0.005	11.12	319.38	27.31	357.81	11.12	180.98	8.27	200.37
0.010	11.12	412.01	34.76	457.89	7.78	253.15	8.60	269.53
0.020	11.12	766.44	41.65	819.21	7.78	389.12	32.13	429.03

Conditions: ΔP_{TM}= 26.46 kPa, u = 0.29 m/s, P = 25 W

Unit of resistance: x10^6 (1/cm)

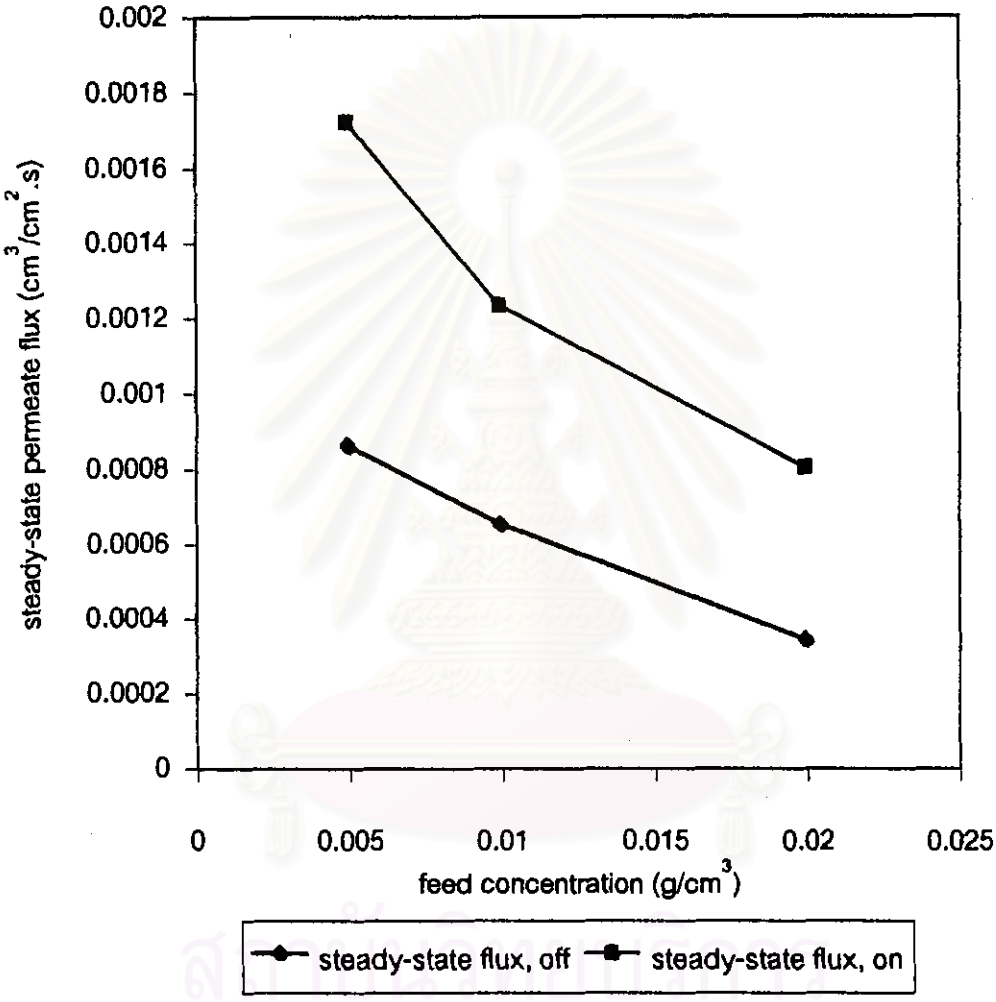


Figure 5-4: Permeate flux of yeast suspension as a function of feed concentration

- Operating temperature of 30℃
- Applied pressure of 26.46 kPa
- Feed flow velocity of 0.29 m/s

5.4 Effect of the sound frequency on the permeation performance

The microfiltration coupling with ultrasonic irradiation was carried out using four transducers attached to the outer surface of the housing as the sound sources of four frequencies; 19.8, 21.5, 23.8 and 30.0 kHz (equivalent to the acoustic wavelength of 7.6, 7.0, 6.3 and 5.0 cm., respectively). Ultrasound was applied to the system at the power of 25 W. The applied pressure and the feed flow velocity were held constant at 26.46 kPa and 0.29 m/s, respectively. The distance between the ultrasonic source and the membrane was also fixed.

In general, ultrasonic frequencies between 20 to 50 kHz are used in the cleaning application though there are experimental data attesting to the fact that intense cavitation is still observed in a liquid at frequencies of 8 to 10 kHz. The reason is that at these low frequencies, a noise problem becomes essential. In addition, it is also difficult to drive a high-frequency transducer assembly at the vibrational amplitudes (intensities) required[12]. Consequently, in our experiments, effect of the sound frequency on permeate flux was studied in the frequency range of 18 to 30 kHz.

It is found that increase in sound frequency in the range between 19.8 to 30.0 kHz hardly effected the permeate flux as demonstrated in Figure 5-5. The slightly increase in permeate flux due to the increasing sound frequency can be explained by the study of the pressure amplitude reduction displaying along the axis from the sound source (Equation (3-24)). A sketch of the axial acoustic pressure behavior at various frequencies is shown in Figure 5-6. The pressure responses of those frequencies display the same characteristic, i.e., decreasing as the distance from the radiation source increasing. It is indicated that the intensity (Intensity = $P_A^2/2\rho c$) of the wave was attenuated with the increasing distance. Consideration of the pressure amplitude at any positions from the source yields that the increase in the sound frequency, (i.e. decrease in the wavelength), resulted in the higher pressure amplitude. Therefore, the strongest cleaning activity over the membrane surface would have produced by the ultrasonic

frequency of 30 kHz as against other three frequencies, and hence, resulting in the highest permeate flux observed from the experiments.

Table 5-7: Effect of the sound frequency on permeate flux and permeation resistance

sound frequency (kHz)	permeate flux ($cm^3/cm^2.s$)	R_m	R_c	R_p	R_t
0	0.00086	11.12	319.38	27.31	357.81
19.8	0.00105	9.43	257.26	11.75	278.44
21.5	0.00108	9.16	242.40	18.28	269.84
23.8	0.00112	9.02	233.82	17.16	260.00
30.0	0.00116	9.43	227.01	18.67	255.11

Conditions: ΔP_{TM}= 26.46 kPa, u = 0.29 m/s, C_b = 0.005 g/cm^3, P = 25 W

Unit of resistance: $x10^6$ (1/cm)

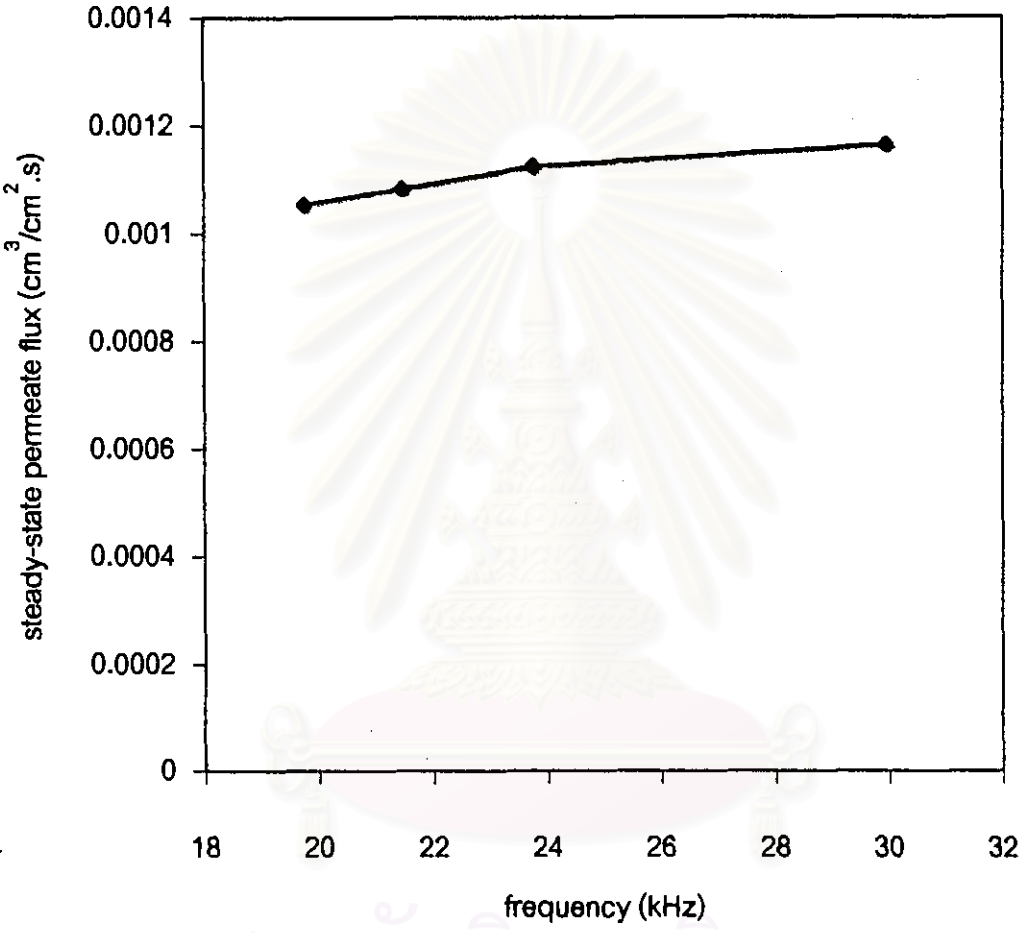


Figure 5-5: Effect of sound frequency on permeate flux

- Operating temperature of 30°C
- Applied pressure of 26.46 kPa
- Feed flow velocity of 0.29 m/s
- Feed concentration of 0.00 5 g/cm^3
- Input power of 25 W

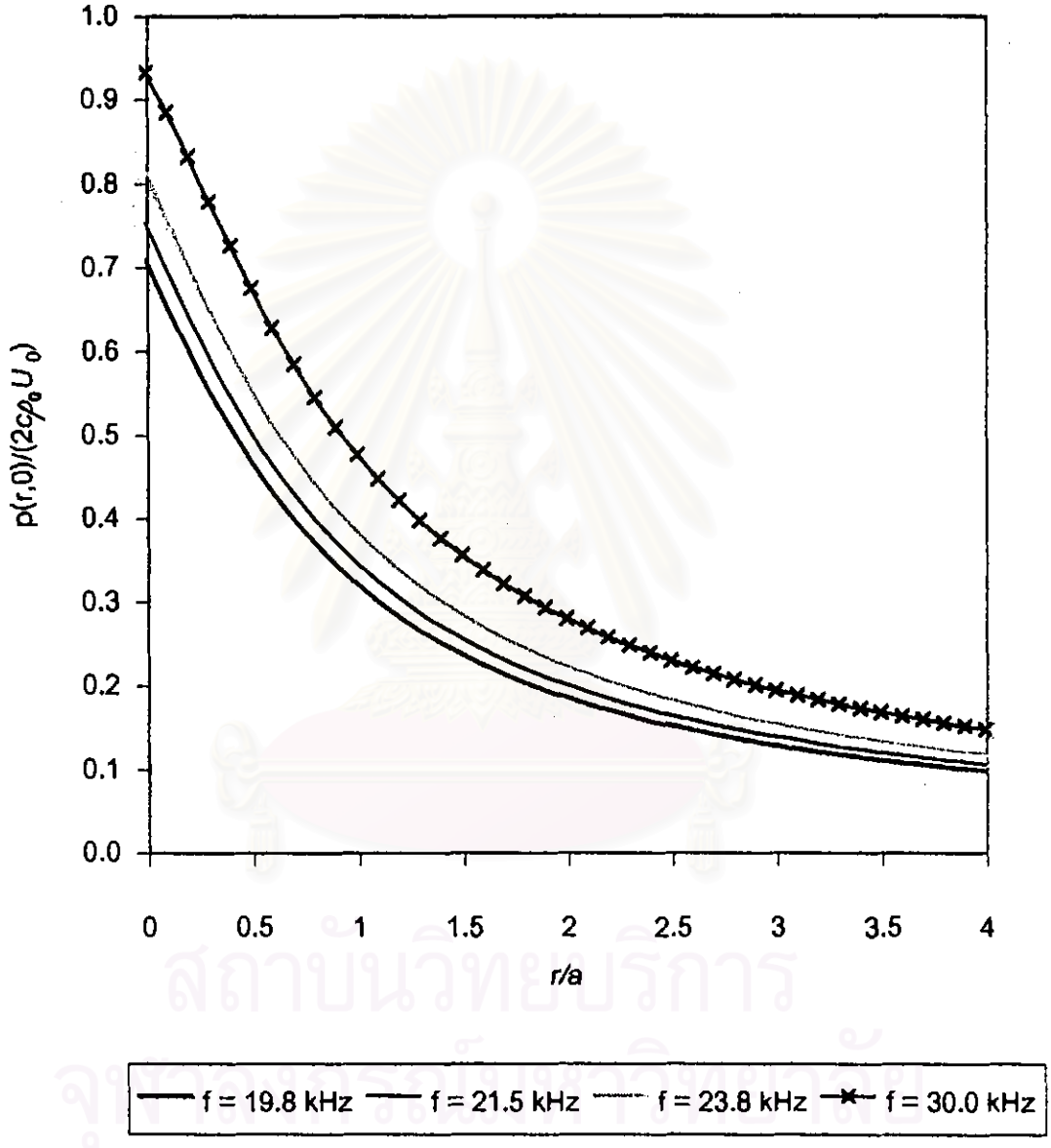


Figure 5-6: On-axis response of transducers of various frequencies

5.5 Effect of the sound intensity on permeation performance

Under the applied pressure of 26.46 kPa and the feed flow velocity of 0.29 m/s, a set of experiment was carried out on studying the effect of five intensities; 0.91, 1.77, 2.19, 2.68 and 3.53 W/cm^2. For comparison, the permeate flux obtained in the case that ultrasound was not applied (intensity = 0 W/cm^2) was also studied.

It was found that permeate flux was increased with increasing sound intensity as expressed in Figure 5-7. This finding follows the fact that an increase in intensity would increase the acoustic pressure, P_a ($P_a = P_A \sin 2\pi ft$) as expressed in Equation (3-18), thereby more cavitation bubbles were performed in the liquid medium. Moreover, bubble collapse would be more violent since both the collapse time (Equation (3-19)), the pressure (Equation (3-14)) and the temperature (Equation (3-15)) on collapse are dependent on P_m ($=P_h + P_a$). However, it is expressed that increasing of intensity in the later stage slightly increased the permeate flux. This occurred from the fact that as sound intensity is increased, the bubble may grow so large on rarefaction that the time available for collapse is insufficient (Equation (3-15)) so there comes more large numbers of stable cavitations instead of the complete collapse to obtain the maximum violent effect. Taking the permeation resistance expressed in Table 5-8 into consideration, it is found that the permeation resistance would hardly be reduced with the increasing intensity in the later stage. So the limited amount of permeation resistance would be reduced by the sound intensity.

Table 5-8: Effect of the sound intensity on permeate flux and permeation resistance

sound intensity (W/cm^2)	permeate flux ($cm^3/cm^2.s$)	R_m	R_c	R_p	R_t
0	0.00086	11.12	319.38	27.31	357.81
0.91	0.00157	19.46	140.47	29.95	189.88
1.77	0.00172	19.46	128.13	28.28	175.81
2.19	0.00194	17.29	119.90	24.22	161.41
2.68	0.00202	16.38	93.47	22.05	131.90
3.53	0.00209	14.15	93.32	20.63	128.10

Conditions: ΔP_{TM}= 26.46 kPa, u = 0.29 m/s, C_b = 0.005 g/cm^3

Unit of resistance: $x10^6$ (1/cm)

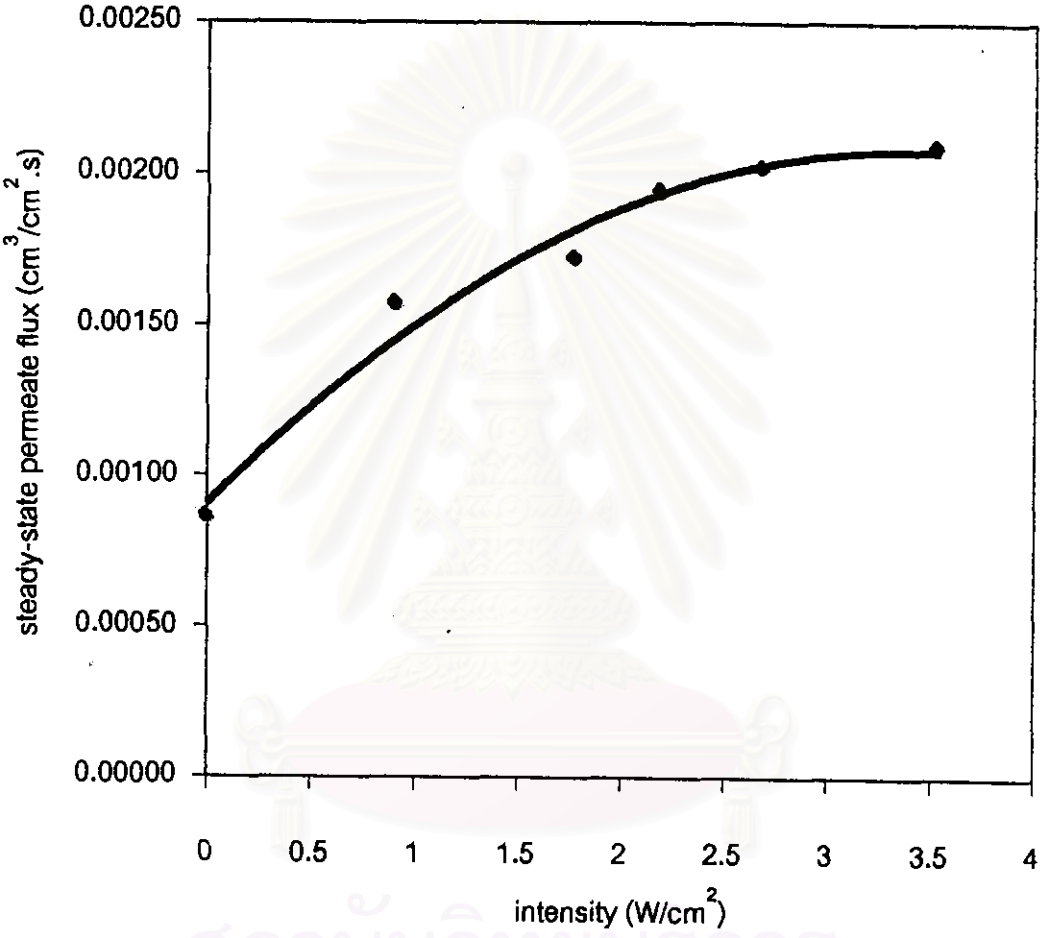


Figure 5-7: Effect of sound intensity on permeate flux

- Operating temperature of 30℃
- Applied pressure of 26.46 kPa
- Feed flow velocity of 0.29 m/s
- Feed concentration of 0.005 g/cm^3

5.6 Effect of the irradiation time

The ultrasound at the power of 25 W was applied to microfiltration of yeast suspension at different time; at 2^{nd}, 6^{th}, 10^{th}, 20^{th} minute after starting the filtration. To examine when the flux improvement by ultrasound occurred, the permeate flux measurement was taken every 15 seconds. It is observed that the increase of permeate flux after the application of ultrasound had no trend as shown in Figure 5-8. Moreover, it cannot predict the exact time when permeate flux will be improved by the introduction of ultrasound in a short period of time (4 minutes). These findings can be explained that an introduction of ultrasound into the microfiltration (in a short period of time) acted as a disturbance to the system, so that the response (increasing flux) back depends not only on the disturbance itself, but also on the condition of the system (microfiltration mechanism) at that time. In addition, the application of ultrasound to the system in the prior period after starting filtration (in 2^{nd}, 6^{th} and 10^{th} minute) caused the more obviously increasing permeate flux as the compaction of cake layer is still in the low level. The observation of the increase in permeate flux affected by ultrasound shows that the response of the ultrasonic cleaning of our system is so slow that the observation of permeate flux expressed no increase in 20^{th} minute of filtration. To investigate whether ultrasonic irradiation can enhance the permeate flux after the cake is compacted over the membrane, consequently, the steady permeate flux is observed, the application of ultrasound in 60^{th} minute after starting filtration was performed for 20 minutes. The increasing flux was expressed within 4 minutes and then fluctuated. This expresses that ultrasound can remove the cake buildup even at the strong compaction of cake layer, but the response of the ultrasonic cleaning of our system is slowly occurred. Thus, the application of ultrasound in a short period of time will slightly affect the flux increase. The flux can be increased under ultrasonic irradiation in case that the suitable duration is applied whether or not the cake layer was formed. In Figure 5-9, permeate fluxes in the case that ultrasound was introduced since the beginning were compared to those observed without ultrasound. It is shown that the permeate flux with an introduction of ultrasound was higher because the destruction of cake layer was continually taken by

ultrasound. However, the application of ultrasound since the beginning of filtration gives rise to the increase in operating costs.

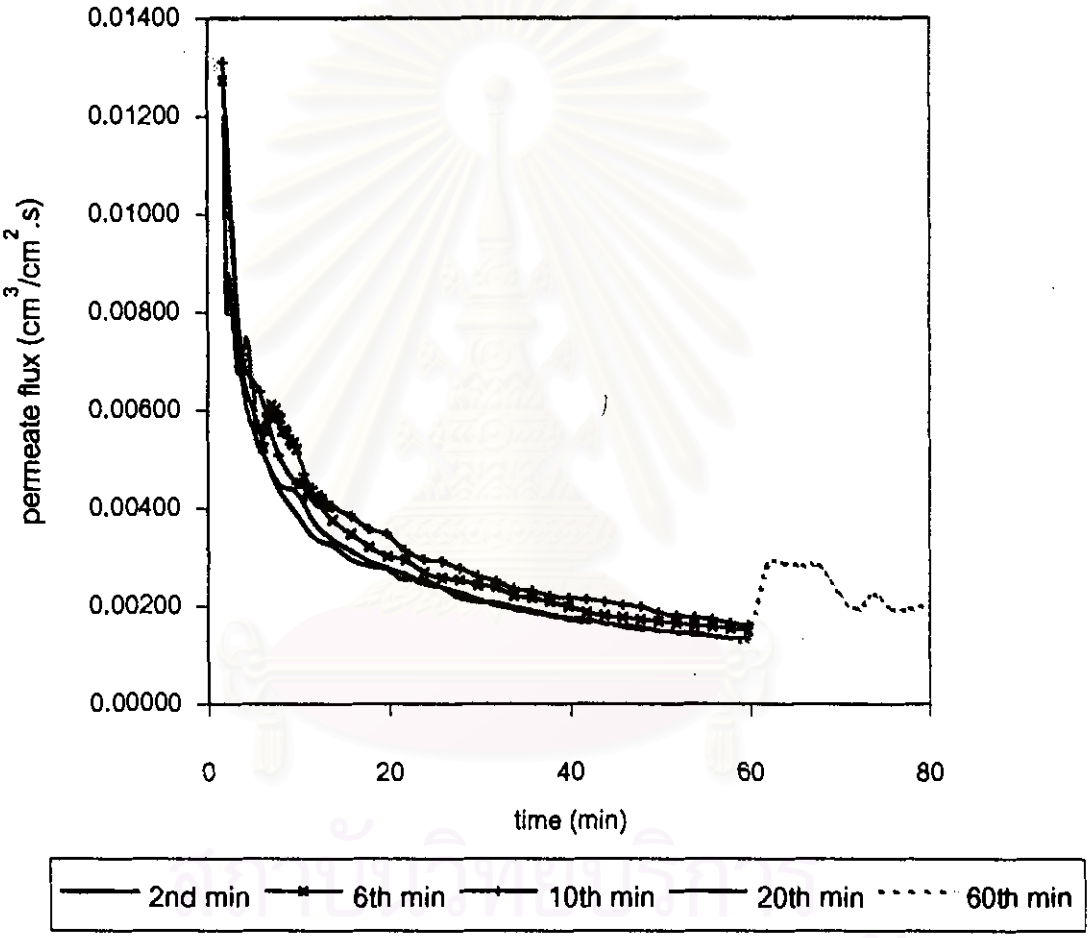


Figure 5-8: Relationship between permeate flux and time at various time of ultrasonic application

- Applied pressure of 26.46 kPa
- Feed flow velocity of 0.29 m/s
- Input power of 25 W
- Duration time of 4 minutes

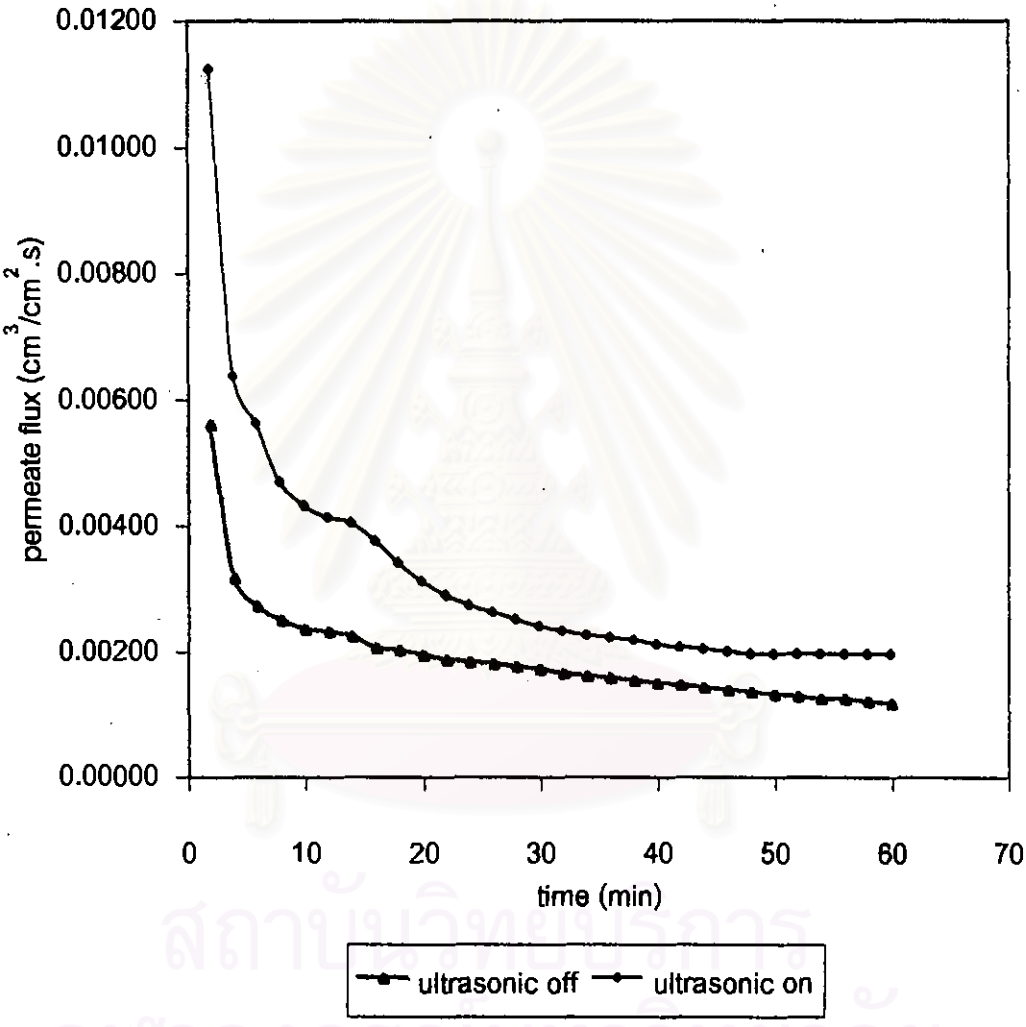


Figure 5-9: Permeate flux of microfiltration with and without ultrasound

- Applied pressure of 26.46 kPa
- Feed flow velocity of 0.29 m/s
- Input power of 25 W

5.7 Effect of the ultrasonic irradiation on the membrane

The membrane used in the experiments is a tubular ceramic membrane. The membrane has an asymmetric structure which consists of two layers, i.e. the actual membrane layer and the porous sublayer. Before the installation with the filtration unit, the membrane was reduced its thickness to lessen the sound energy absorption. Consequently, the membrane structure was examined using the study of Scanning Electron Microscope (SEM) and the pore size of the membrane was also investigated using Mercury Porosimetry measurement. After being used in the process of microfiltration coupling with ultrasonic irradiation for a period of time, the retention property of the membrane was changed and the indentation was observed at the membrane surface, illustrated in Figure 5-10, as a result of ultrasonic irradiation. Investigation of the effect of ultrasonic irradiation on the sonicated membrane was therefore taken by using the measurements previously described.

5.7.1 Scanning Electron Microscope

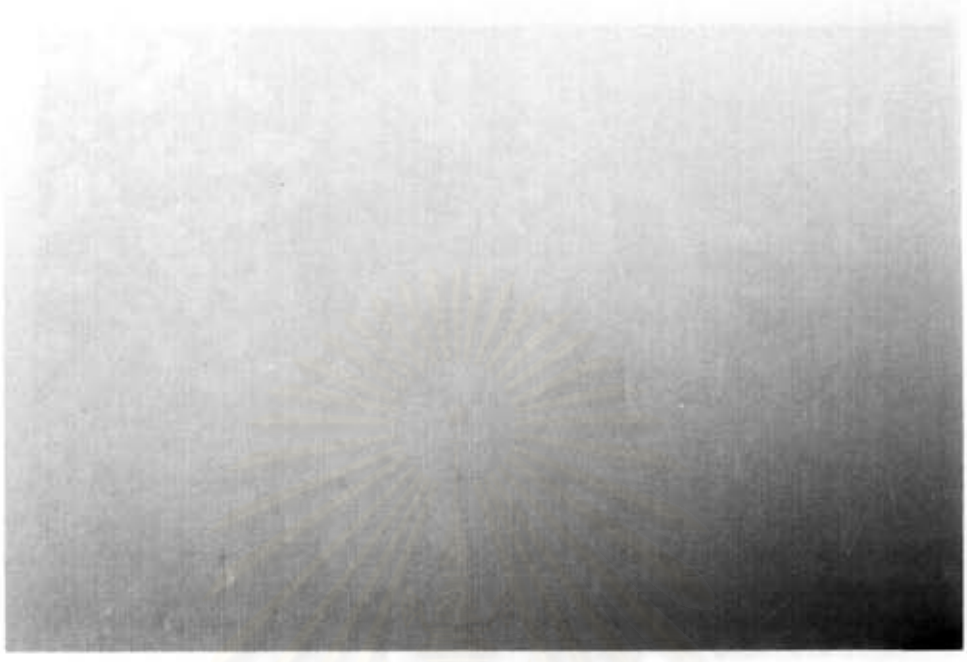
Taking the SEM photographs in Figure 5-11 into consideration, the membrane after being reduced the thickness presented only the porous sublayer. After being sonicated for a long period of time, it is observed a greater amount of open pores over the membrane structure.

5.7.2 Mercury Porosimetry

As the analysis of the SEM photograph of the structure of the membrane after being reduced its thickness indicated that the remaining membrane consisted of the only porous sublayer. The measurement of the pore diameters of the membrane before and after being sonicated examined by using the Mercury Porosimetry expressed the median pore diameter of 1.89 and 2.25 microns, respectively. This finding advocates that with the long irradiation period, microimpact destruction of cake layer also caused the destruction to the membrane, thereby larger pore diameter shown.

Since the membrane structure was changed with the effect of ultrasonic irradiation, the permeation resistance should also be changed. The larger pores illustrated, the less permeation resistance should be demonstrated. This assumption was proved by taking the various resistance in filtration in Table 5-8 into consideration. It is found that the slightly decrease of the membrane resistance, R_m, and the plugging resistance, R_p, with the increase of sound intensity. This can be explained as the more power applied, the stronger cavitational collapse at the solid surface, consequently, expressed the more indentation, and hence both observed resistance showed the decreasing value. However, the irradiation time was an alternate parameter which affects both resistance. It was found that the longer sonicated, the more indentation expressed. Comparison of the total resistance observed form the membrane resistance, R_m, the plugging resistance, R_p, and the cake resistance, R_c, it is obviously shown the much higher value of the cake resistance than of the others. Although R_m and R_p were also reduced by ultrasonic irradiation, the decrease of those values compared with the decrease of R_c by ultrasound is still much lower. In conclusion, it is reasonable to say that ultrasonic irradiation allows an increasing permeation performance of microfiltration.

In the experiments, the membrane resistance, R_m, was measured before starting the filtration and was used to be a criteria of changing the membrane. The membrane would be change if the decrease of its resistance in the larger value compared to that before being sonicated was observed.



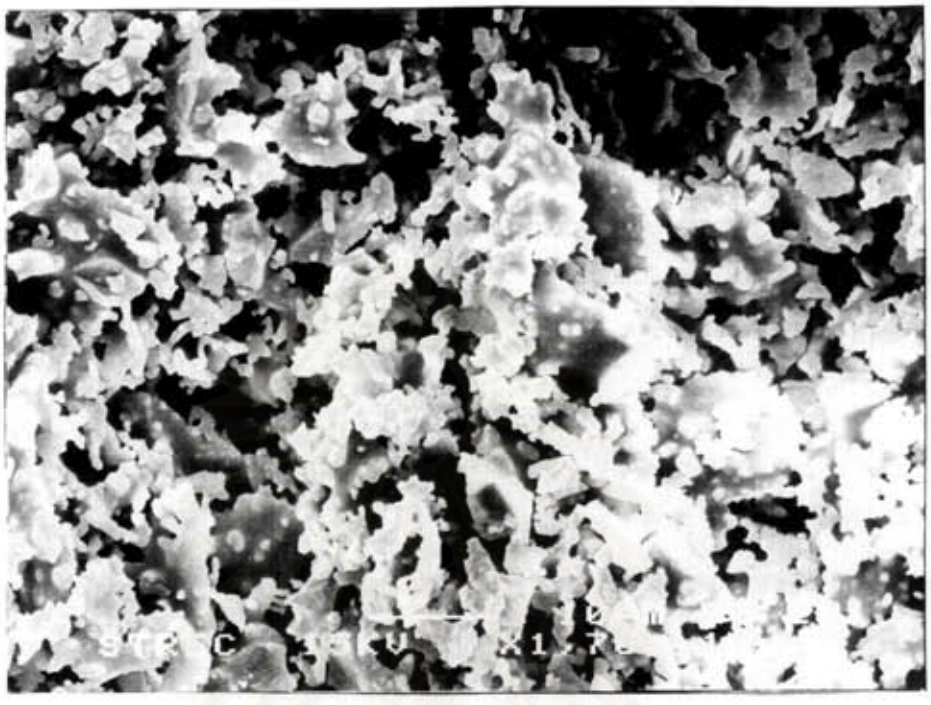
(a)

(b)

Figure 5-10: The surface of the membrane

(a) before being sonicated

(b) after being sonicated



(a)

(b)

Figure 5-11: SEM study of cross-sectional structure of the membrane

(A) before being sonicated (B) after being sonicated

5.8 Effect of the ultrasonic irradiation on the yeast

The purpose of the study of the ultrasonic effects is mainly on the change in size and size distribution of the yeast cells. The yeast used in the experiments was considered to serve as particles which would not grow, i.e. no change in the morphology and their size distribution throughout a batch of running (1.5-3.5 hours) due to lacking of culture medium and improper pH. However, ultrasonic effect to their growths was also studied.

Experiments to study the ultrasonic effects on the yeast were examined in three ways: microscope observation, particle size analyzer and cell cultivation. The characteristics of microfitration were set up at the applied pressure of 26.46 kPa, the feed flow velocity and the feed concentration of 0.29 m/s and 0.005 g/cm^3, respectively. Ultrasound was applied to the filtration at the power of 40 W as it is the highest power generated by the made transducers. Microfiltration coupling with ultrasonic system was carried out to study the morphology and particle size distribution of the yeast affected by ultrasonic irradiation. The yeast broth in the feed tank was sampled at 30th, 60th and 90th minutes after starting the filtration to study the change in cells morphology (using the microscope observation) and their cultivation capability (cultivating in agar-based medium). In addition, five samples mentioned in section 4.5.3 were cultivated in the agar-based medium to investigate the numbers of cells that were destroyed by the ultrasonic irradiation (without filtration) and to elucidate the factor caused the ruptured cells. The particle size distribution of the yeast cells affected by ultrasonic irradiation was examined between three samples, i.e. the yeast suspension without processing, the yeast suspension after being sonicated at a very high intensity (50 W/cm^2) and the yeast suspension after being pumped at the highest feed flow velocity (0.48 m/s).

5.8.1 Microscope observation

The yeast used in the experiments is *Saccharomyces cerevisiae* species. Consideration the morphology of yeast cells using the microscope observation at the

magnification of 400 found that the cells are generally round as demonstrate in Figure 5-12 (a). The sampling of these cells from the feed tank after being filtrated with ultrasonic irradiation at different periods of time expressed no change in cells' morphology and no change of the cells' color from the methylene blue solution added, therefore, the cells were still alive. In addition, there is no cell debris observed.

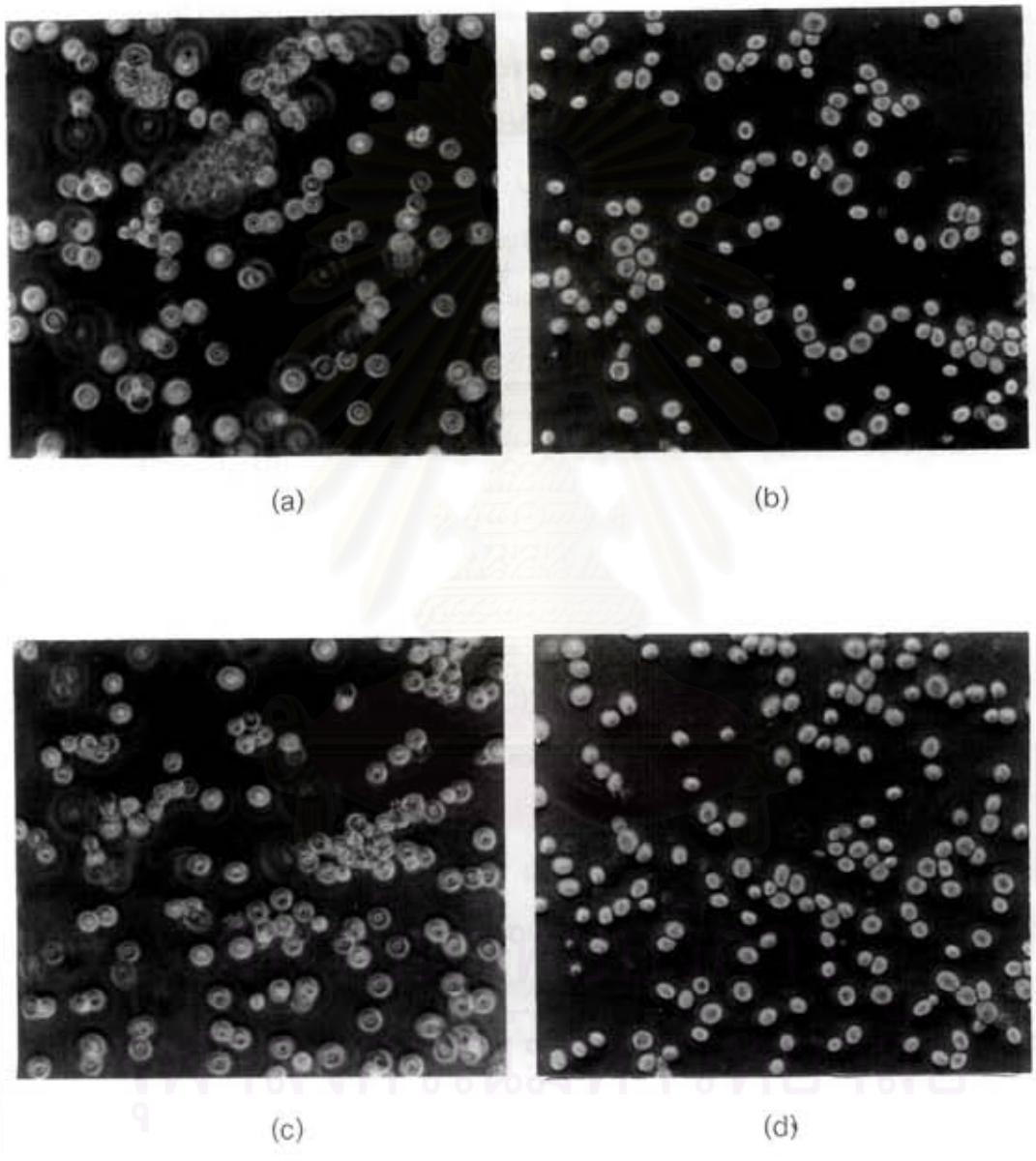


Figure 5-12: Yeast cells at the magnification of 400

(a) before being sonicated

(b), (c), (d) after being sonicated for 30, 60 and 90 minutes, respectively

5.8.2 Particle size analysis

Due to the fact that ultrasound can cause the rupture of cells, thereby cell debris with smaller size than of the normal one is observed. In addition, the high shear rate introduced by high feed flow velocity is an alternative parameter which can cause the damage of cell [2]. Three samples were therefore taken to examine if there was any change on the particle size distribution (cell debris with smaller sizes) during the process of microfiltration with ultrasound in our experiments.

Table 5-9: Samples taken to study the particle size distribution of yeast cells

Sample No.	Sample ID*	pump	acoustic intensity (W/cm^2)	controlled temperature (°C)
1	Sample11	off	0	30
2	Sample8	off	3.6	30
3	Sample4	on	0	30

Note: - Each sample was measure the size distribution at 30^{th}, 60^{th} and 90^{th} minute.

- The sampling at 30^{th}, 60^{th} and 90^{th} minute of operation represents as Run Number 1, 2 and 3 (Appendix C), respectively.
- * = Sample ID represents in the experimental data shown in Appendix C.

Particle size distribution of these samples are expressed in Figure 5-13, 5-14 and 5-15. The measurement of the cells taken from Sample No. 1 expressed the average size of 7 microns and the wide range of size distribution. Actually, single cell is 1-10 microns in diameter [2,10,14]. The larger size than 10 microns observed might be the agglomeration of cells into colonies (see Figure 5-12 (a)). After being sonicated for 30, 60 and 90 minutes at the intensity of 3.6 W/cm^2 (which is the highest intensity generated by the made transducers) under the controlled temperature of 30 °C (Sample No.2), the narrower size distribution was expressed, and this was thought to be occurred as a result of the more dispersion induced by ultrasonic irradiation. However, the smaller size than 1 micron was not expressed. This indicates that there was no change in the cell size affected by ultrasonic irradiation at the intensity of 3.5 W/cm^2 or

less. Similarly, the observation of the particle size distribution of the cells after being pumped (at the highest flow rate performed by the centrifugal pump used in our experiments) under the controlled temperature of 30 °C (Sample No.3) shows the particle size distribution of 1-10 microns at every sampling time.

Obviously, there was no change of particle size distribution due to the highest intensity generated by the made transducers or the highest feed flow velocity introduced by the pump used in the experiments. Therefore, there was no effect of the change of particle size distribution on the microfiltration coupling with ultrasonic irradiation at any conditions in our experiments.

5.8.3 Cultivation in agar-based medium

The experiments were divided into 2 parts as previously described in Chapter IV. In the first part, the cultivation capability of yeast cells from the filtration system after being sonicated was examined compared to those without ultrasonic irradiation. Samples of yeast broth, taken from the feed tank at 30^{th}, 60^{th} and 90^{th} minutes after starting filtration, could be cultivated in agar-based culture medium as shown in Figure 5-16. In the second part, since the cells are rupture by either high intensity of ultrasound or high temperature generated by ultrasonic irradiation, five samples of yeast cells, illustrated in Table 5-10, were therefore taken to investigate these effects individually. In the case that yeast cells can be grown, white opaque cells with round rim will be observed over the culture medium. It is found that only Sample No. 1 and No. 2 (the same condition as in our experiments) that could be cultivated, and there was no difference in morphology and numbers of cells expressed, illustrated in Figure 5-17 (a) and (b). Whereas, the cultivation of another three samples in the same medium and pH observed no cells, expressed in Figure 5-17(c). These findings advocate that cell disruption is mainly occurred by the influence of high temperature. However, a very high intensity can also cause the cells disruption according to no observed cell from Sample No.3, though the system was controlled at room temperature (30 °C).

Therefore, it can be concluded that the yeast cells after being processed with ultrasonic irradiation in our experiments were not destroyed and can be cultivated in the proper medium.

Table 5-10: The cultivation capability of the yeast cells taken from various conditions

Sample No.	acoustic intensity (W/cm^2)	temperature of yeast suspension (°C)	Numbers of cells expressed
1	0	30	63
2	3.6	30	63
3	100	30	0
4	100	73	0
5	0	73	0

Note: Operating time = 1 hour, Volume of sample taken = 0.1 cm^3, Dilution rate = 10^{-5}

5.9 Rejection of the membrane

The method of concentration analysis used in the experiments was the measurement of cell number as previously mentioned in section 4.6. The membrane used in the experiments is an asymmetric tubular ceramic membrane with the pore size of 0.9 microns. As described in section 5.7, the remaining mambrane consisted of the only porous layer with the median pore diameter of 1.89 microns. Particle size distribution of the yeast cells is between 2-10 microns. As permeate and retentate were recirculated to the feed tank, the feed concentration was assumed to be constant within the whole process. The sampling of permeate to measure the number of yeast cells every 10 minutes while the filtration was processing observed no cells at any conditions of microfiltration. Consequently, the rejection of the membrane, calculated from Equation (3-12) and (3-13), was 100 %.

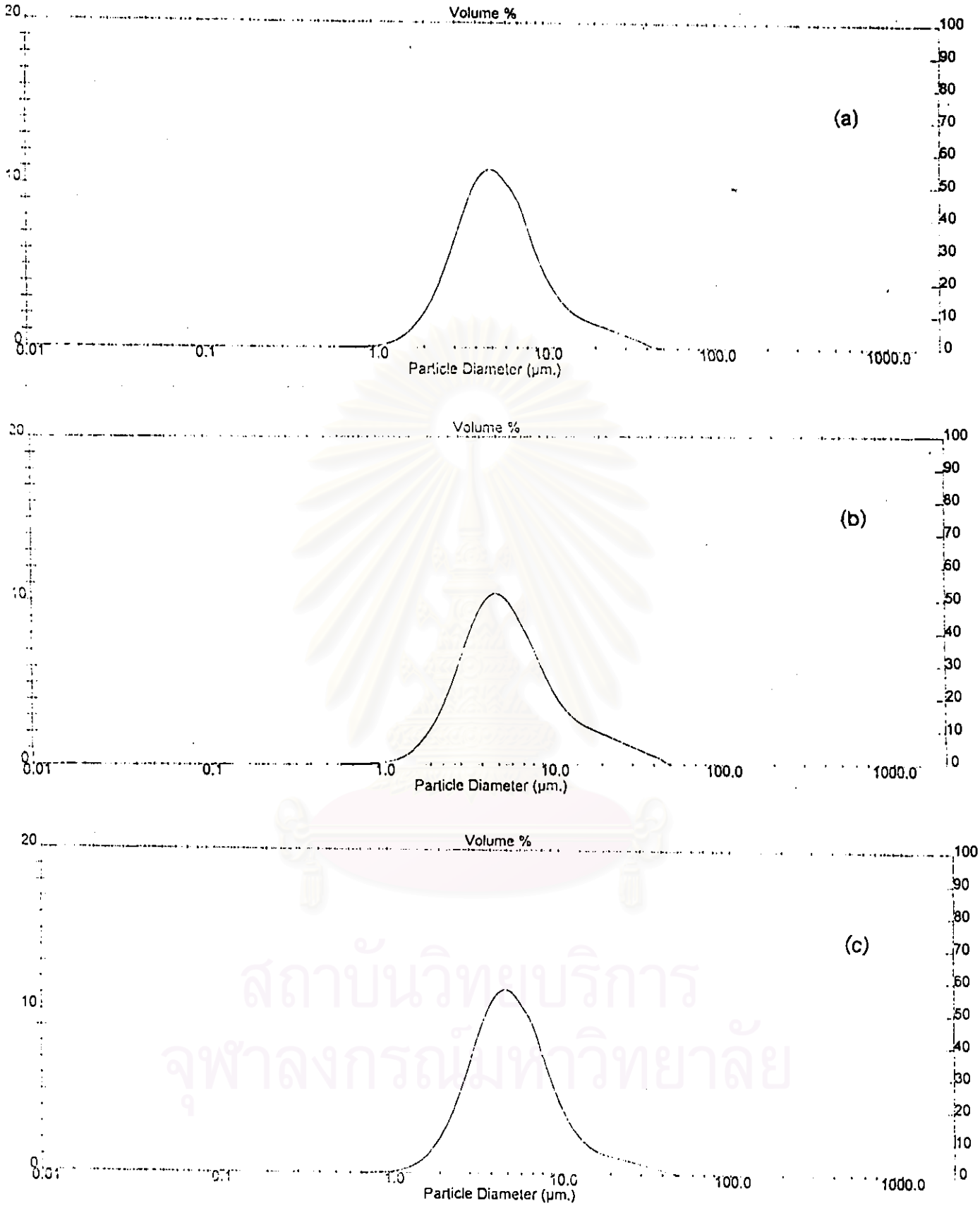


Figure 5-13: Particle size distribution of yeast cells without processing (sampling at (a) 30th, (b) 60th and (c) 90th minute after being prepared)

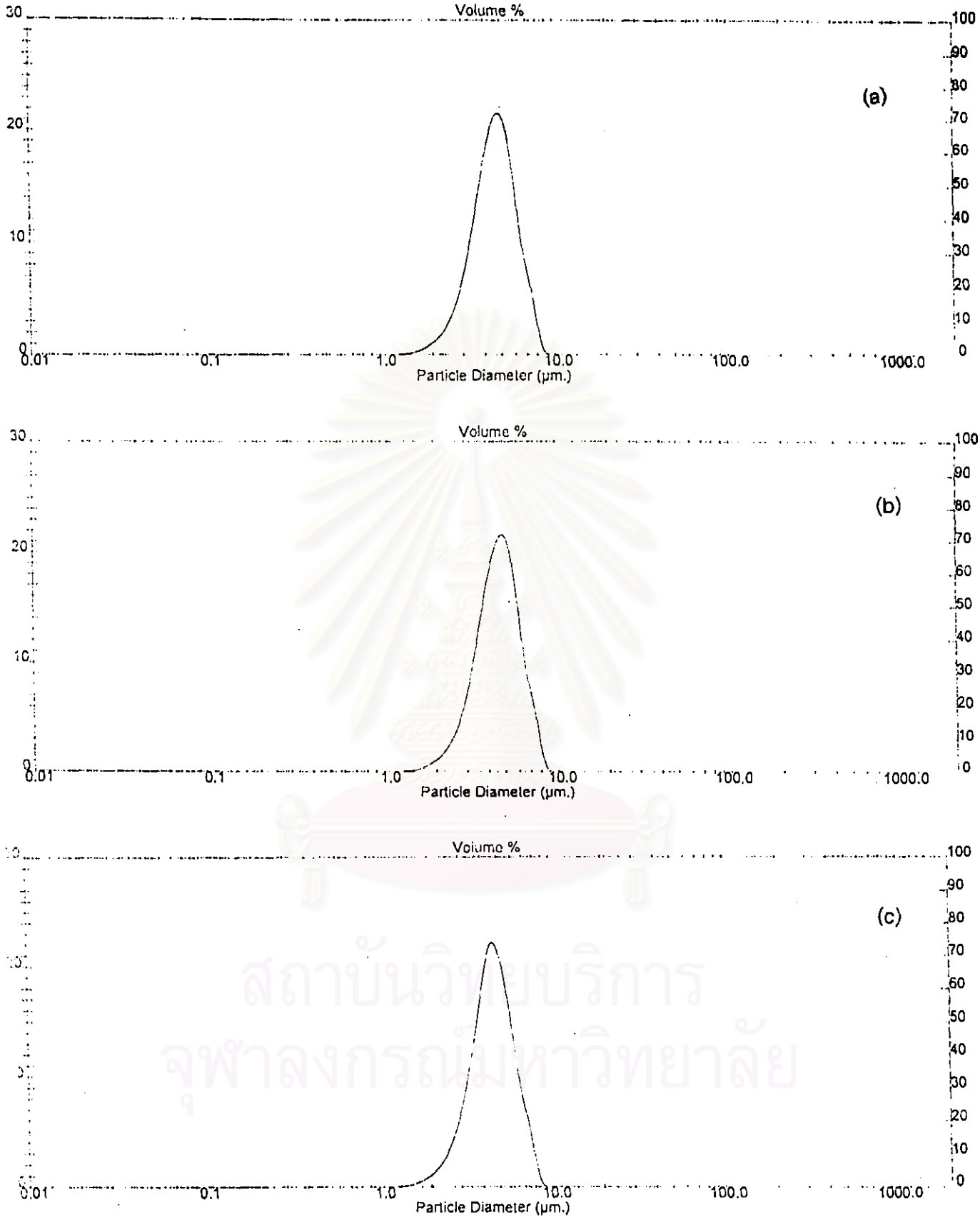


Figure 5-14: Particle size distribution of yeast cells after being sonicated at high intensity (sampling at (a) 30th, (b) 60th and (c) 90th minute after being sonicated)

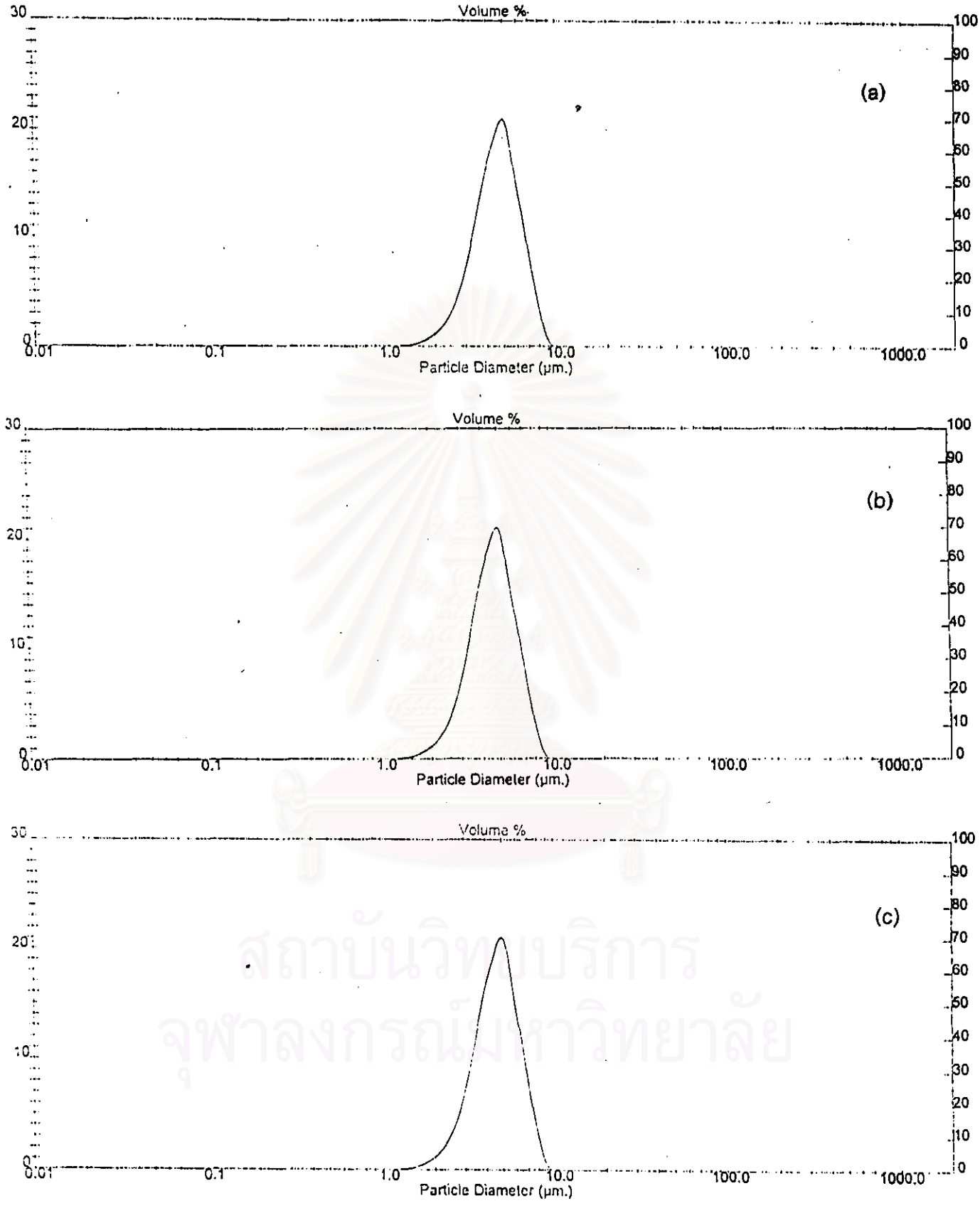
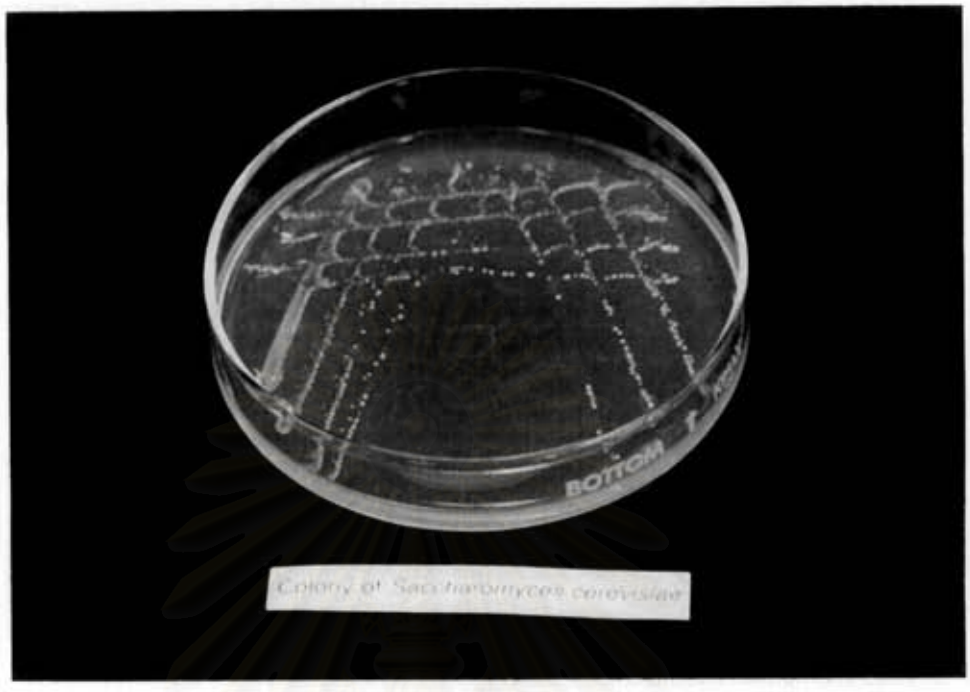
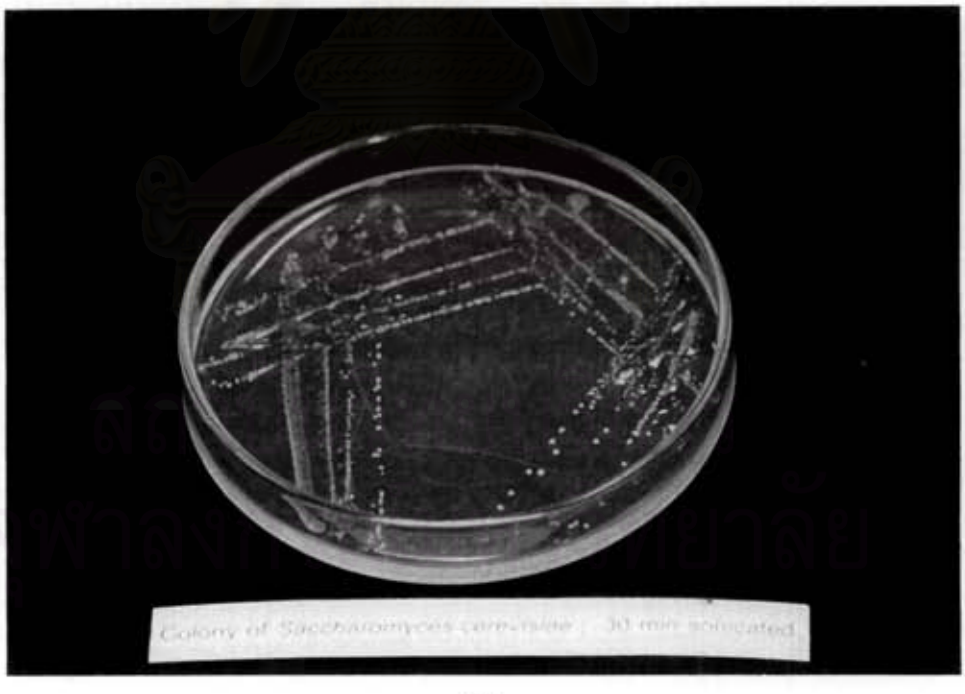


Figure 5-15: Particle size distribution of yeast cells after being pumped at high velocity (sampling at (a) 30th, (b) 60th and (c) 90th minute)



(a)

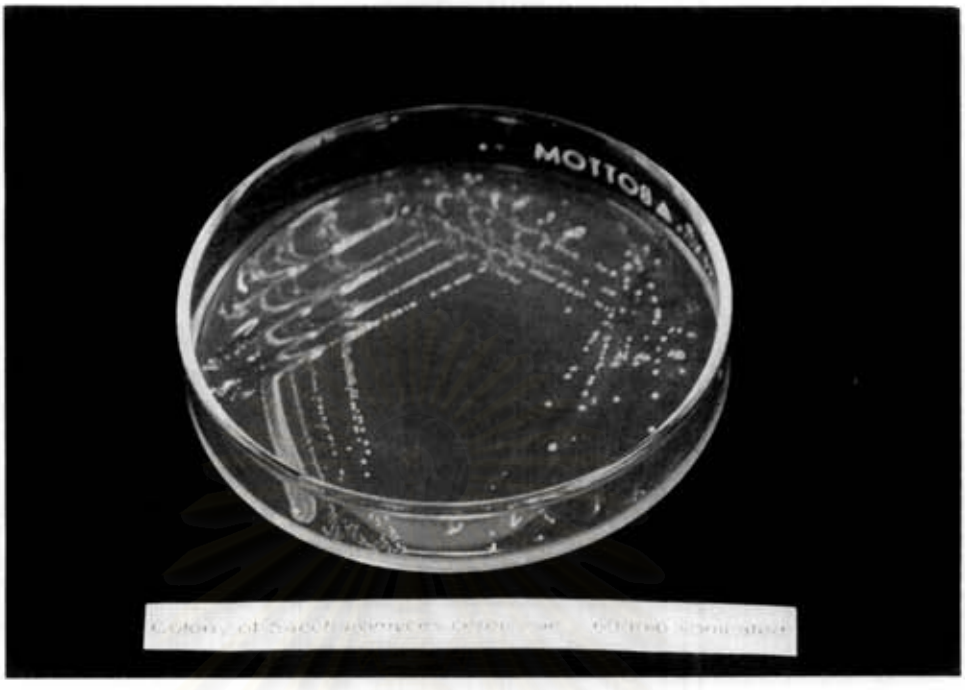


(b)

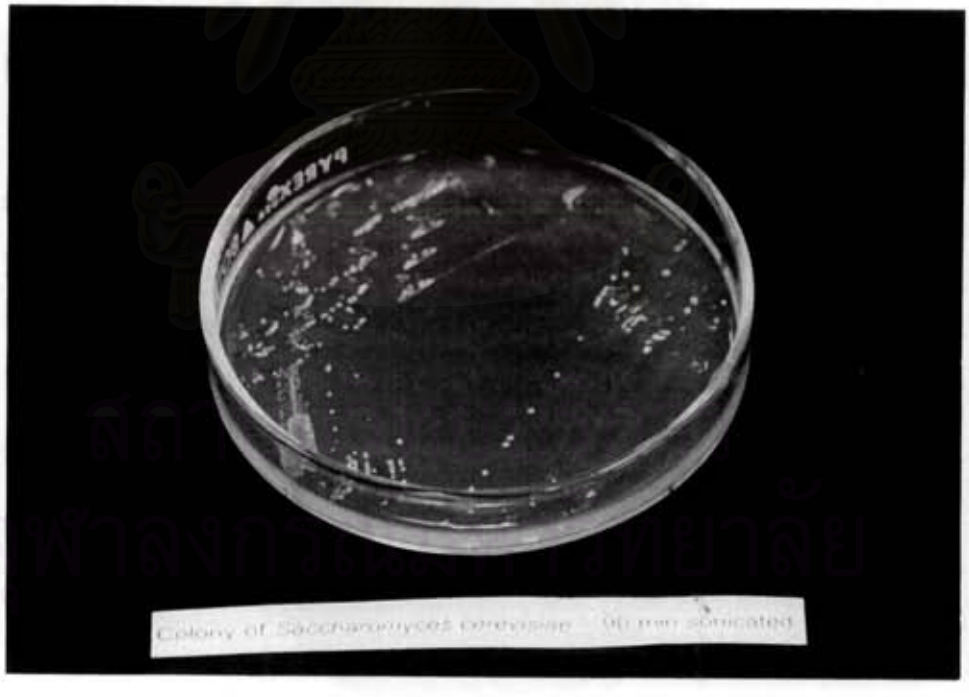
Figure 5-16: Colonies of *Saccharomyces cerevisiae*

(a) before being filtration coupling with ultrasonic irradiation

(b) after being filtration coupling with ultrasonic irradiation for 30 min.

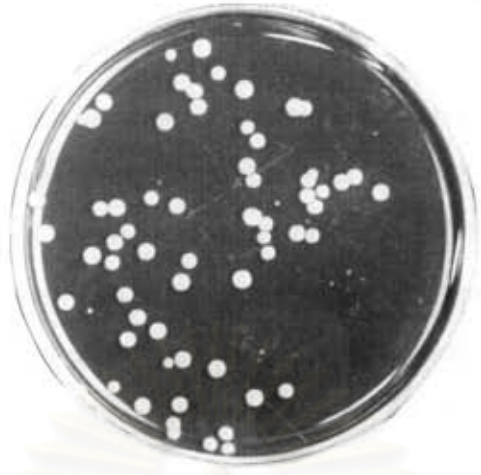


(c)



(d)

Figure 5-16 (continue): Colonies of *Saccharomyces cerevisiae* after being filtration coupling with ultrasonic irradiation for (a) 60 minutes (b) 90 minutes



(a)

(b)

(c)

Figure 5-17: Yeast cells cultivated in agar-based medium taken from

(a) Sample No.1 (b) Sample No.2 (c) Sample No. 3, 4, 5 (Table 5-10)

5.10 Economic analysis

In this section, the economic analysis of the microfiltration coupling with ultrasonic irradiation was briefly discussed neglecting the cost resulted from the membrane damage. Due to the absence of the best result obtained from microfiltration without ultrasound, the comparison between these two systems (conventional and ultrasonic systems) were then based on our experimental data which were taken from Table C-3 and Table (c-4). If the operating time is assumed to be at 8 hours a day, and 30 days of operation per month, then operating hours per month are 240 hours. The operating costs of the conventional system and the ultrasonic ones are shown in Table 5-11. It is expressed that ultrasonic system can save the operating cost per unit volume of permeate. However, the introduction of ultrasound into the conventional system leads to the increasing costs. The capital cost of our ultrasonic system depends on equipment costs, costs of maintenance and installation costs as expressed in Table 5-12.

To investigate the return on investment, the calculation by dividing the capital cost of the ultrasonic system (17,740 Bahts) with the saved operating cost (0.0018 Baht/cm^3 of permeate) is reported in the value 9,855,555 cm^3. In an hour of operation, a permeate was filtrated in the value of 1,512 cm^3, so that to return on investment, microfiltration with ultrasonic irradiation for 6,518 hours (or 9 months) must be operated.

Since the very low rate of filtration, it is found that to return on investment of the only 18,000 Bahts, 9 months of the operation is required. Therefore, it can be concluded from this comparison that ultrasonic system is suitable for the filtration system with the low filtration rate in order to reduce the filtration time of the small volume of permeate without the matter of the low investment cost. Nevertheless, it is still impractical at this stage to obtain any final economic conclusions on the application of ultrasound into the microfiltration system. The comparison between the conventional and our proposed systems must be considered.

Table 5-11: Operating costs of conventional and ultrasonic systems

	conventional system	ultrasonic system
Pumping system		
- Units of electricity	88.8	88.8
- Costs of electricity per month (Baht)	355.2	355.2
Acoustic supplied system		
- Units of electricity	0	12
- Costs of electricity per month (4 Bahts/unit)	0	48
Total costs of electricity (Baht/month)	355.2	403.2
Volume of permeate in a month (cm^3)	120,960	362,880
Operating costs (Baht/$cm^3$of permeate)	0.0029	0.0011
Saved costs (Baht/$cm^3$of permeate)		0.0018

Note: - Steady-state permeate flow rate observed from microfiltration with and without ultrasonic irradiation are 0.14 and 0.42 cm^3/s, respectively.

- Units of electricity = W x (operating hours in a month)/1,000

- 0.37 kW pump and 2x25 W transducers are used.

Table 5-12: Estimation of capital requirements

Capital cost of the ultrasonic system	Total cost (Baht)
1. Equipment	
1.1 Transducers	5,600
1.2 Electrical Supplied System	7,800
1.3 Miscellaneous	3,000
2. Installation (5% of equipment costs)	670
3. Maintenance (5% of equipment costs)	670
Total cost	17,740