CHAPTER V

RESULTS AND DISCUSSIONS

5.1 Effect of pervaporation membrane type on performance of SOFC system

In this section, the performance of SOFC system using pervaporation with two different membrane types, namely hydrophilic and hydrophobic membranes has been investigated as depicted in Figure 5.1. In principle, although bioethanol as a dilute ethanol solution was suitable for hydrophobic type due to lower energy consumption for a small amount of ethanol removal, this membrane type was inevitable to face the limitation of low ethanol separation factors as shown in Figure 5.1. It may perform a low ethanol recovery or obtain ethanol concentration below the target level (25 mol% ethanol). On the contrary, a hydrophilic type may assist to reach the desired ethanol concentration owing to high water separation factors, although it requires high energy supply to remove plenty of steam. Therefore, it is necessary to compare the performance between hydrophilic and hydrophobic membrane for pervaporation and their effects on the overall SOFC system performance.

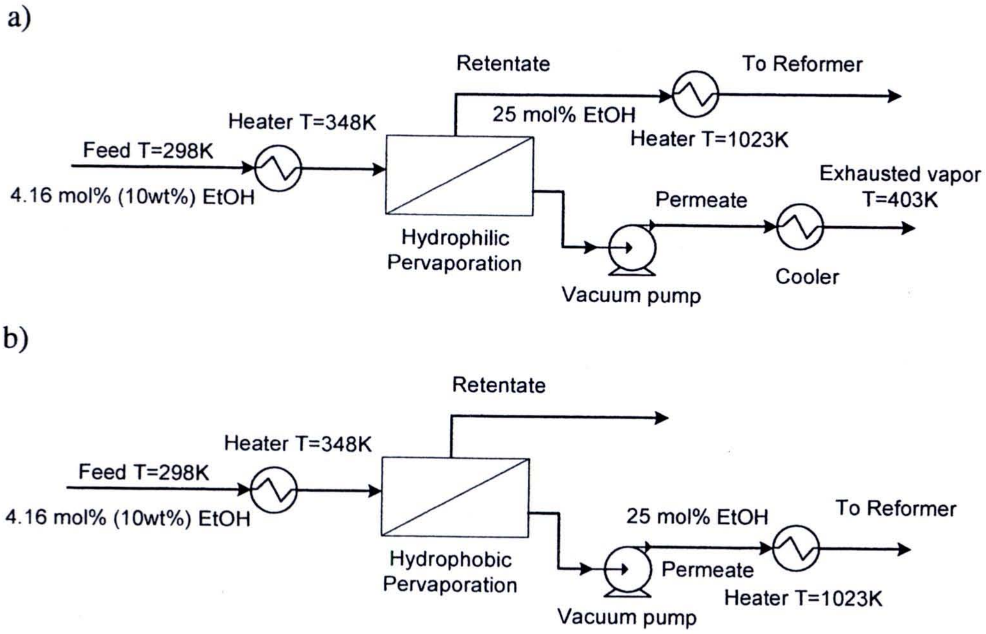


Figure 5.1 Pervaporation membrane type configurations: a) Hydrophilic and b) Hydrophobic

According to Figure 5.1, for case a), a hydrophilic pervaporation was used to remove excess water from the feed by permeating through a membrane until the retentate side of the pervaporation contained 75 mol% water. The heat accumulated in steam on the permeate side was recovered to supply the heater operated at 1023K until its exhausted temperature reached 403 K to redeem a high thermal energy consumption in this case. When considering case b), ethanol was permeated by hydrophobic pervaporation to obtain a permeate stream of 25 mol% ethanol.

Table 5.1 A review of separation performance with different membrane types of pervaporation unit

<table>
<tr><th colspan="5">Hydrophobic membrane</th></tr>
<tr><th>Membrane material</th><th>Ethanol in feed (wt%)</th><th>Temperature (K)</th><th>Separation factor ($\alpha_{E/W}$)</th><th>Reference</th></tr>
<tr><td>Silicalite-1/α-Al_2O_3</td><td>5</td><td>348</td><td>78</td><td>Lin et al. (2001)</td></tr>
<tr><td>Silicalite-1/Mullite</td><td>10</td><td>333</td><td>72</td><td>Lin et al. (2000)</td></tr>
<tr><td>PDMS</td><td>10</td><td>348</td><td>6.25</td><td>Baker et al. (2010)</td></tr>
<tr><td>PTMSP(-silica)</td><td>10</td><td>348</td><td>10.7</td><td>Gonzalez-Velasco et al. (2003)</td></tr>
<tr><td>PDMS(ZSM-5 mixed matrix)</td><td>10</td><td>348</td><td>15.5</td><td>Baker et al. (2010)</td></tr>
<tr><td>ZSM-5/α-Al_2O_3</td><td>10</td><td>348</td><td>24</td><td>Kita (1998)</td></tr>
<tr><th colspan="5">Hydrophilic membrane</th></tr>
<tr><th>Membrane material</th><th>Water in feed (wt.%)</th><th>Temperature (K)</th><th>Separation factor ($\alpha_{W/E}$)</th><th>Reference</th></tr>
<tr><td>Zeolite NaA, disk</td><td>90</td><td>303</td><td>>10000</td><td>Kumakiri et al. (1999)</td></tr>
<tr><td>Cellulose ester</td><td>90</td><td>348</td><td>0.76</td><td>Baker et al. (2010)</td></tr>
<tr><td>NaA, Mullite/Al_2O_3</td><td>10</td><td>348</td><td>42000</td><td>Kondo et al. (1997)</td></tr>
</table>

5.1.1 Separation characteristics of hydrophilic and hydrophobic membranes

Figure 5.2 presents the values of required separation factor in order to purify dilute bioethanol to 25mol%ethanol at any specified ethanol recovery (*R%*). It was found that the required separation factor increased following by increasing ethanol recovery especially at high ethanol recovery. In addition, Figure 5.2 also expresses the corresponding permeate flow rates in each membrane type. For the hydrophobic type, the desired ethanol product is at the permeate stream while for the hydrophilic type the ethanol product is at the retentate stream. The results show that when using the hydrophilic membrane a large amount of water are needed to be removed to the permeate side (more than 240 kmol/s) to obtain a desired ethanol composition in the retentate stream, in contrast to a hydrophobic type, much smaller amount of its permeate flow rates are required to achieve a desired ethanol removal. Different amount of permeate flow rates obtained in each membrane type can convey to the required energy including electrical power of vacuum pump and total thermal energy at different ethanol recovery as illustrated in Figures 5.3a) and 5.3b) for hydrophilic and hydrophobic types, respectively. It can be seen that both total thermal energy and power of vacuum pump increase consistently when increasing an ethanol recovery.

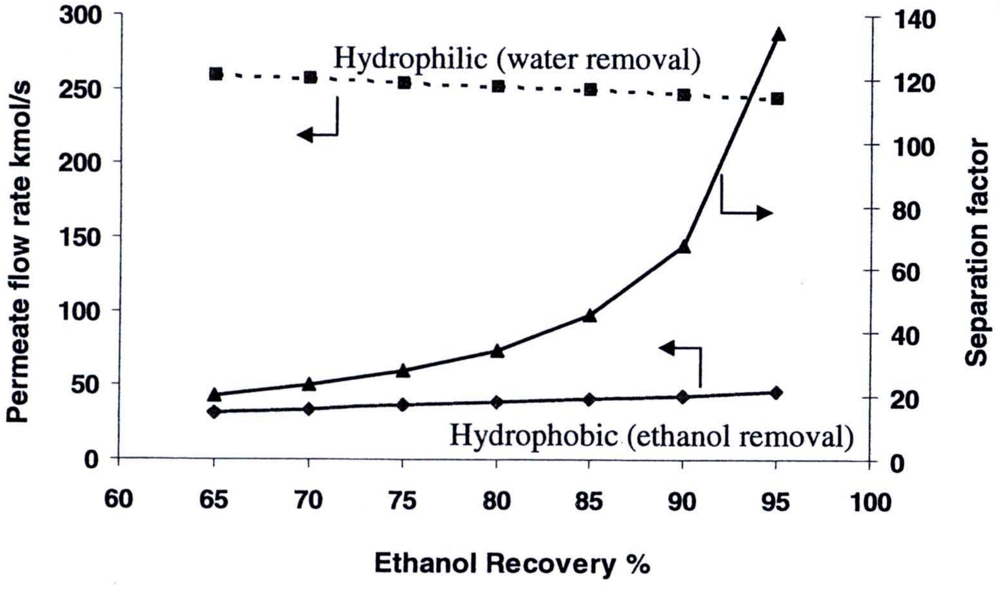
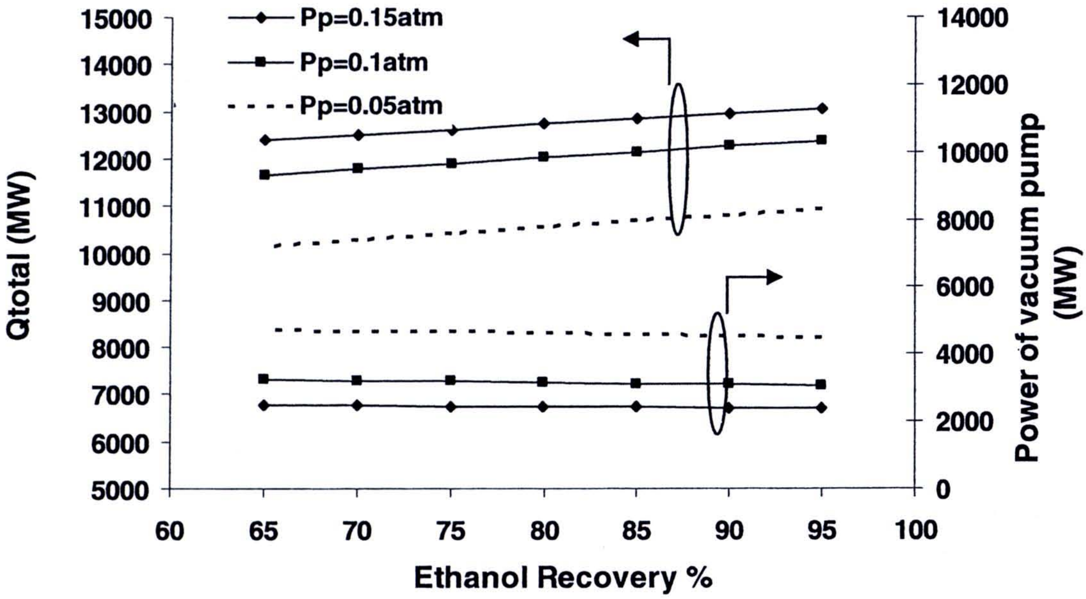


Figure 5.2 Effect of ethanol recovery on the separation factor and flow rates.

a)



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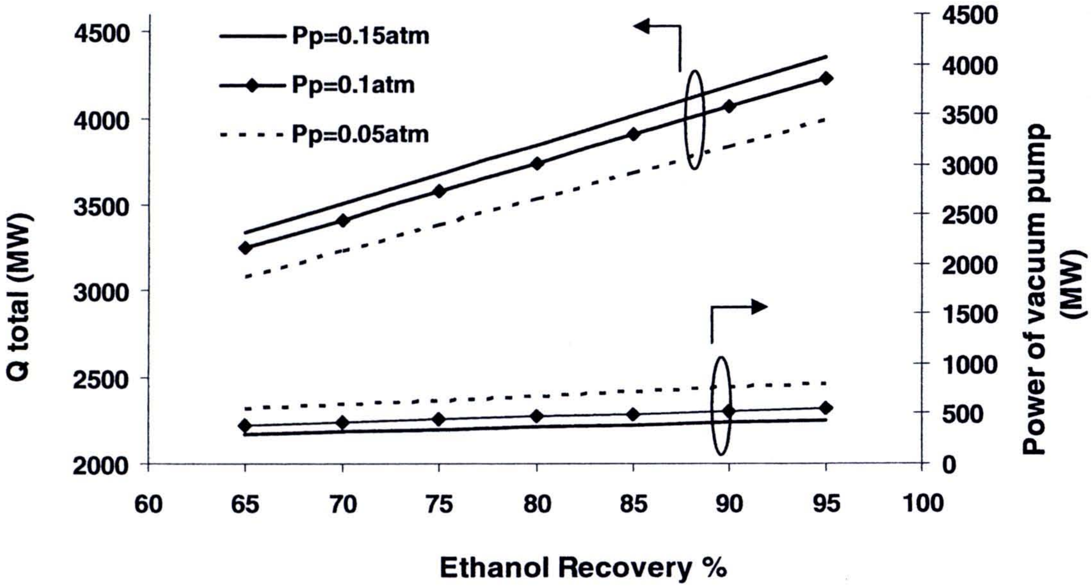


Figure 5.3 Effect of ethanol recovery on the total thermal energy and power of vacuum pump consumption for: a) hydrophilic and b) hydrophobic membranes.

When comparing between two membrane types, it is apparent that the hydrophilic type in Figure 5.3a) uses about 3-4 times of thermal energy higher than that of the hydrophobic type shown in Figure 5.3b) because it requires plenty of heat for vaporizing a large amount of water as indicated in Figure 5.2. It also utilizes more power at the vacuum pump according to the same reason. From Figure 5.3, there is an inverse relationship between total thermal energy and power of vacuum pump. When the permeate pressure was reduced, the vacuum pump consumed more electrical power and the permeate temperature became higher as represented by Eq. (4.6). Due to the higher permeate temperature, it can reduce burden of heater located prior to the reformer required to heat up to 1023 K so the total thermal energy becomes lower. Although the hydrophobic type required energy much less than the hydrophilic type, the separation factor values obtained in Figure 5.2 available for the hydrophobic type can serve only at low ethanol recovery ranges while these from the hydrophilic type can be available even at high ethanol recovery as shown in Table 5.1.

5.1.2 Performance assessment of SOFC system using pervaporation with two different membrane types

After discovering the characteristic results of both membrane types from the previous studies, evaluation of overall performance of SOFC system using both membrane types based on the net energy were performed and the results are shown in Figure 5.4. It is found that an increase of fuel utilization brought about the decrease of net energy in all cases.

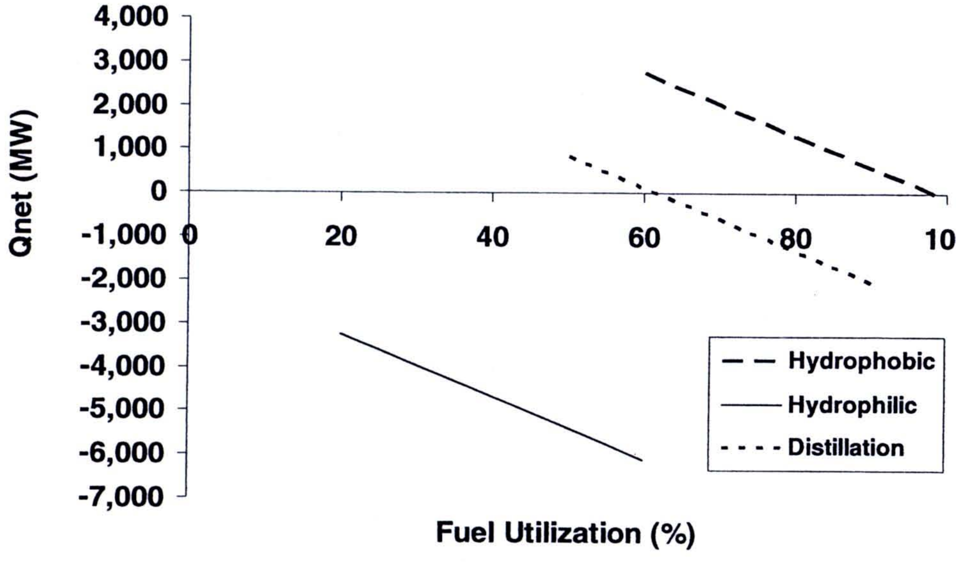


Figure 5.4 Effect of fuel utilization on the net energy (Q_{net}) of SOFC system with two different membrane types of pervaporation and distillation column ($R_{EtOH} = 85\%$, $V = 0.6V$, $T_{SOFC} = 1073K$, $P_p = 0.15atm$).

The low operating voltage of 0.6V is specified in order to have some fuel utilization values which assist the system especially hydrophilic case to be operated at least $Q_{net} = 0$. At this condition, the external heat sources are not required but the results indicate that it is impossible to operate the SOFC system with hydrophilic pervaporation at this condition. A distillation column is considered as having poorer performance than a pervaporation which is then compared with the other two membrane types (Figure 5.4) to demonstrate that it can be operated below $Q_{net} = 0$ and offers its performance superior to hydrophilic membrane type. Therefore, a hydrophobic type still becomes a suitable alternative for purifying bioethanol regarding a lower energy consumption.

5.1.3 Performance characteristics of SOFC system integrated with hydrophobic pervaporation

According to the previous studies, the use of hydrophobic pervaporation with the SOFC system can be operated without external energy demand. The operating conditions of hydrophobic pervaporation are further investigated to show the performance characteristics of the overall system based on $Q_{net} = 0$.

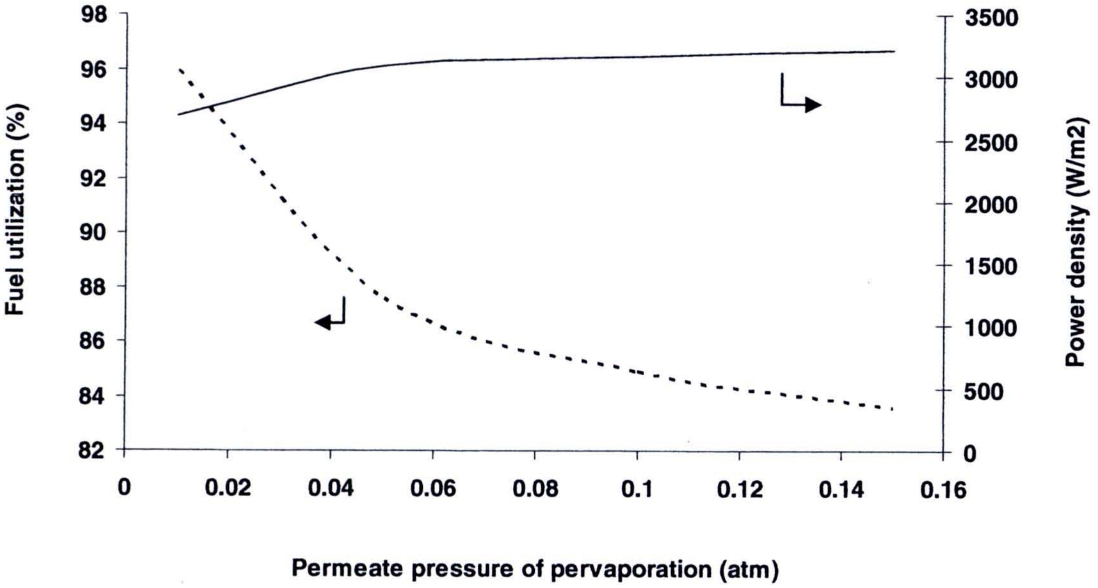


Figure 5.5 Effect of permeate pressure of pervaporation on fuel utilization and power density of SOFC system based on $Q_{net} = 0$ ($R_{EtOH} = 80\%$, $V = 0.7$V, $T_{SOFC} = 1073$K).

Since a pervaporation unit required electrical power to operate a vacuum pump apart from its thermal energy requirement, the effect of operating permeate pressure on SOFC system needs to be studied. Figure 5.5 shows the results of fuel utilization and power density of SOFC at different permeate pressure values. When a vacuum pump operates at lower permeate pressures, it consumes more electrical power to support its conditions, but the temperature of permeate stream becomes higher. It can reduce burden of a heater located prior to the reformer operated at 1023 K because of higher heat accumulated in the permeate stream. Consequently, SOFC system operated under $Q_{net} = 0$ must consume more fuel for converting into electricity as represented with increasing a fuel utilization especially at low permeate pressure on Figure 5.5. This reduces an amount of the remaining fuel being combusted in the afterburner that releases excess heat, while the power density shows a little effect from decreasing the permeate pressures as the operating voltage was assumed constant at 0.7 V. Regarding the effect of permeate pressure on the overall electrical efficiency, an electrical power consumption of a vacuum pump takes quite no effect in deceasing of the electrical efficiency. It was found that the overall electrical efficiencies from the specified permeate pressure range were obtained at rather the same of 39.36%.

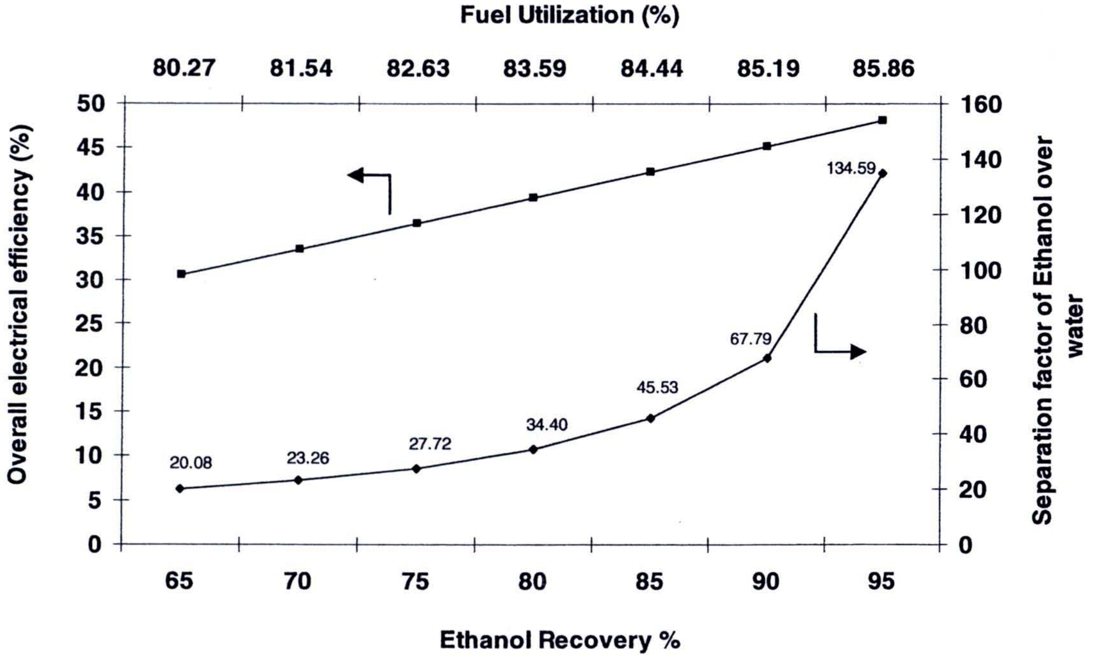


Figure 5.6 Effect of ethanol recovery on the overall electrical efficiency of SOFC system and acquired separation factor using hydrophobic pervaporation based on $Q_{net} = 0$ ($V = 0.7$V, $T_{SOFC} = 1073$K, $P_p = 0.15$atm).

Figure 5.6 shows the performance of SOFC system including the overall electrical efficiency, fuel utilization and $\alpha_{\mathrm{EtOH/Water}}$ at different values of ethanol recovery. The results indicate that when increasing the ethanol recovery, it certainly requires a membrane with much higher ethanol separation factor particularly in the range of 85-95% ethanol recovery, but the system can achieve a higher overall electrical efficiency. At the ethanol recovery of 95%, the system can gain the overall electrical efficiency of almost 50%, although it requires an ethanol separation factor as high as 134.59 and the system also consumes more fuel as described by increasing the fuel utilization values in Figure 5.6. In fact, a hydrophobic membrane which has a high ethanol separation factor to serve this desired ethanol concentration with high ethanol recovery is not available. It is necessary to have other techniques to solve this problem or further assist the separation performance of the hydrophobic membrane.

5.2 Performance improvement of SOFC system with hybrid vapor permeation-pervaporation process

In this section, a pervaporation based on available membrane materials from Table 5.1 is considered as a purification unit for SOFC system fuelled by bioethanol to represent more realistic results. In the first part, the separation efficiency of pervaporation in each membrane material is compared at various values of ethanol recovery. Thereafter, the separation performance is further improved by introducing a vapor permeation installed after the pervaporation to gain a desired ethanol concentration at a higher ethanol recovery. To serve this propose, a selection of appropriate membrane type for vapor permeation is further investigated by considering the membrane availability and optimal overall efficiency.

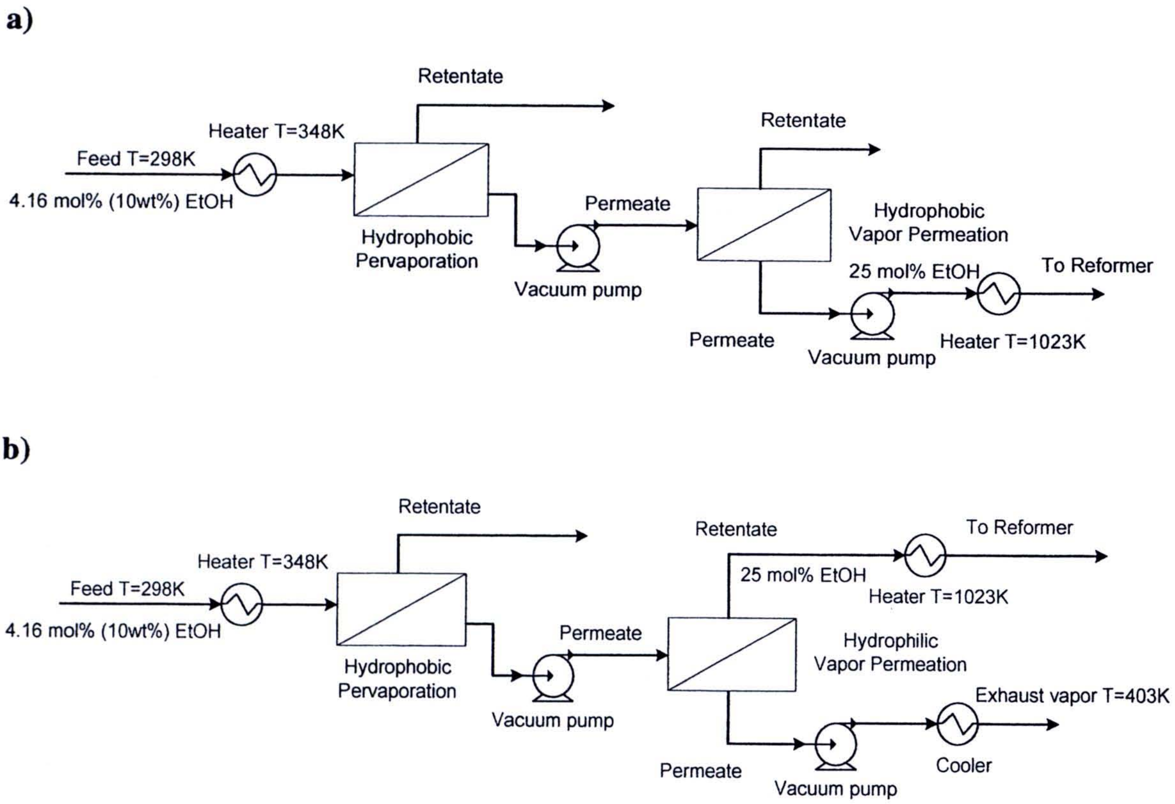


Figure 5.7 Purification process configurations: a) pervaporation with hydrophobic vapor permeation b) pervaporation with hydrophilic vapor permeation

For the SOFC system configurations, various bioethanol purification processes were considered as depicted in Figure 5.7. The pervaporation with hydrophobic vapor permeation and pervaporation with hydrophilic vapor permeation were placed on a) and b), respectively. A hydrophobic membrane was chosen for the pervaporation unit in accordance with the principle mentioned before. Ethanol recovery (R_{EtOH}) of vapor permeation in cases b) and c) were defined at 99%. To consume less electrical power, the vacuum pumps of both pervaporation and vapor permeation were assumed to be operated at 0.15 atm which was feasible in practical operation.

For case a), the hydrophobic vapor permeation was installed after the pervaporation to obtain a permeate stream of 25 mol% ethanol at a higher ethanol recovery. On the other hand, the hydrophilic vapor permeation in case b) was used to remove excess steam permeating through the membrane until the retentate side of the vapor permeation contained 75 mol% water. It was assumed that the heat available in the permeate stream could be recovered until its exhaust temperature reached 403 K (Wassana Jamsak et al., 2007).

5.2.1 Effects of ethanol recovery and membrane material on the obtained ethanol concentration in hydrophobic pervaporation

A separation performance of hydrophobic pervaporation is assessed based on the performance of real membrane materials as summarized in Table 5.1. The selected membranes are PDMS, PTMSP, PDMS (ZSM-5 mixed matrix) and ZSM-5 (α-Al_2O_3) which offer the ethanol separation factor values of 6.25, 10.7, 15.5, 24, respectively. The results illustrate that when increasing the ethanol recovery of pervaporation, the obtained ethanol concentrations from all membranes are declined as illustrated in Figure 5.8. For the membranes with low ethanol separation factor such as PDMS with $\alpha_{E/W}$ = 6.25, the desired ethanol concentration (25 mol%) cannot be achieved at any ethanol recovery even at low recovery values. When consider of the other three membranes, PTMSP membrane with the ethanol separation factor of 10.7, just a little higher than that of PDMS, merely obtains 25 mol% ethanol at 31.16% ethanol recovery. For PDMS(ZSM-5 mixed matrix) and ZSM-5(α-Al_2O_3) membranes, they can provide 25mol%ethanol with more than 50% ethanol recovery (54% and 71%, respectively). At high ethanol recovery such as 95%, Figure 5.8 shows that there is no significant difference in the obtained ethanol concentration among all membranes regardless of membrane separation factor values. As a result of increasing the ethanol recovery, a high ethanol separation factor value for hydrophobic pervaporation should be required to achieve the desired ethanol concentration with high ethanol recovery.

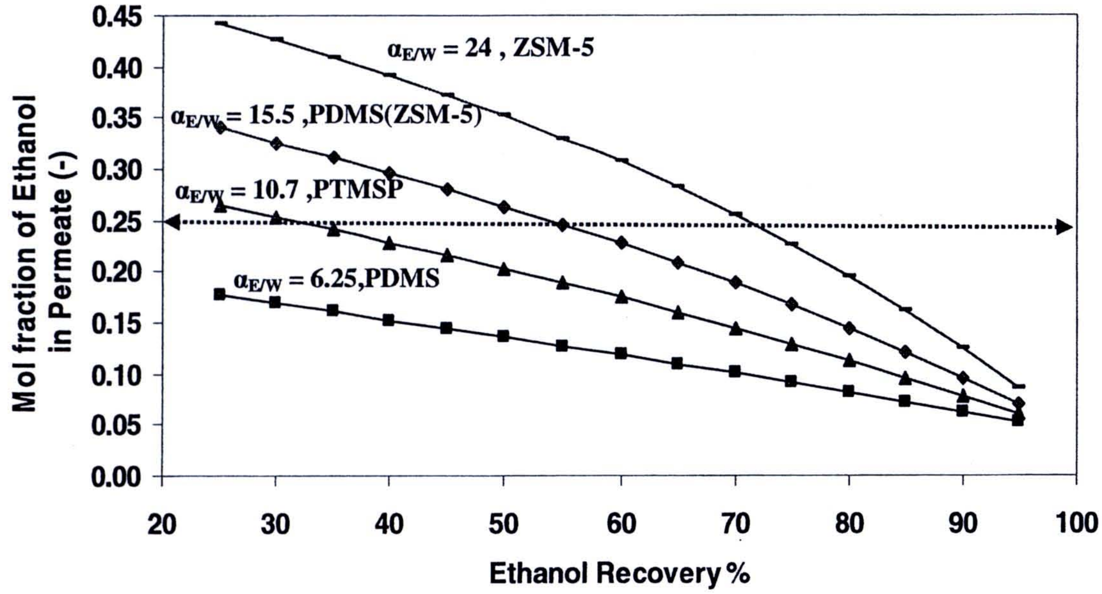


Figure 5.8 Effect of ethanol recovery with various membrane materials on ethanol concentration using hydrophobic pervaporation.

5.2.2 Performance comparison between different vapor permeation membrane types

According to the previous results in Figure 5.8, it is clear that due to the low sepration factor of the hydrophobic membrane for pervaporation, the desired ethanol concentration of 25% can only be achieved with some membrane materials but the obtained ethanol recovery is still low. To improve its poor separation performance, a vapor permeation installed after the pervaporation is proposed. The effect of membrane types (hydrophobic and hydrophilic) is investigated. PTMSP membrane having the lowest ethanol recovery at the desired ethanol concentration which was regarded as the worst case is considered to be a reference case study in this section in order to clearly demonstrate its performance improvement.

5.2.2.1 Effect of pervaporation ethanol recovery on the required vapor permeation separation factor and permeate flow rate

Figure 5.9 shows the permeate flow rates of the hydrophobic and hydrophilic vapor permeations at different values of pervaporation ethanol recovery of PTMSP ($\alpha_{E/W}$ =10.7)-based membrane. The ethanol recovery in a vapor permeation was specified at 99%. It can be observed that the permeate flow rates of the hydrophobic type increase gradually when increasing the pervaporation ethanol recovery. However, for the hydrophilic type whose desired ethanol composition of 25mol% appears at the retentate stream, the permeate flow rate increases rapidly with increasing the pervaporation ethanol recovery. At the low range of pervaporation ethanol recovery, the values are smaller than those of the hydrophobic membrane but the opposite trend is observed at higher ranges of pervaporation ethanol recovery. The upper x-axis of Figure 5.9 showed the obtained ethanol mol fraction in the permeate stream of the pervaporation. The values decline from the desired ethanol concentration when increasing the ethanol recovery to above 31.16%. The right y-axis of Figure 5.9 indicates that it requires a higher membrane separation factor for the vapor permeation when increasing the pervaporation ethanol recovery.

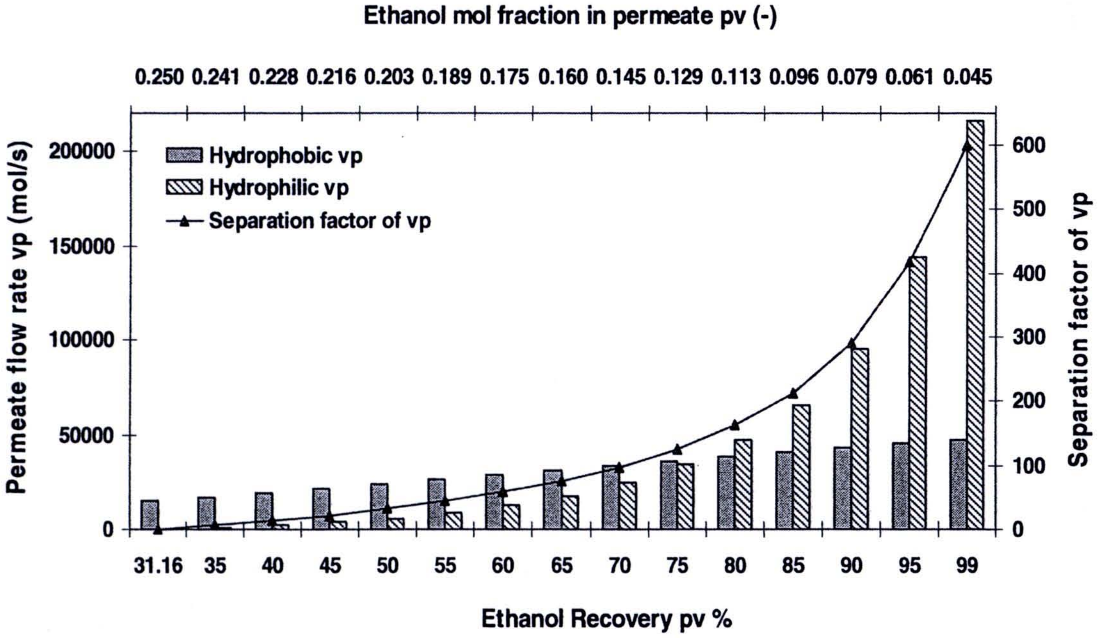


Figure 5.9 Effect of ethanol recovery of PTMSP pervaporation on permeate flow rate between two types and separation factor of vapor permeation.

The value of the vapor permeation separation factor increases above 100 at the ethanol recovery greater than 70%. At a higher range of ethanol recovery (80-99%), both cases require much higher separation factor to achieve their conditions. Based on the principle stated by Wijmans and Baker (1995), they claimed that the permeability data of pervaporation can be applied as a preliminary estimation for vapor permeation. Therefore, from the results shown in Figure 5.9, it indicates that the required ethanol separation factor values for hydrophobic type are not available in commercial membranes. On the contrary, the obtained water separation factor of hydrophilic vapor permeation is available in real membranes according to the high $\alpha_{W/E}$ (Table 5.1).

5.2.2.2 Effect of pervaporation ethanol recovery on energy consumption within vapor permeation

The results of energy requirement including thermal and electrical energy were presented in Figure 5.10. Three SOFC systems (i.e. pervaporation alone, pervaporation with hydrophobic vapor permeation and pervaporation with hydrophilic vapor permeation) were considered.

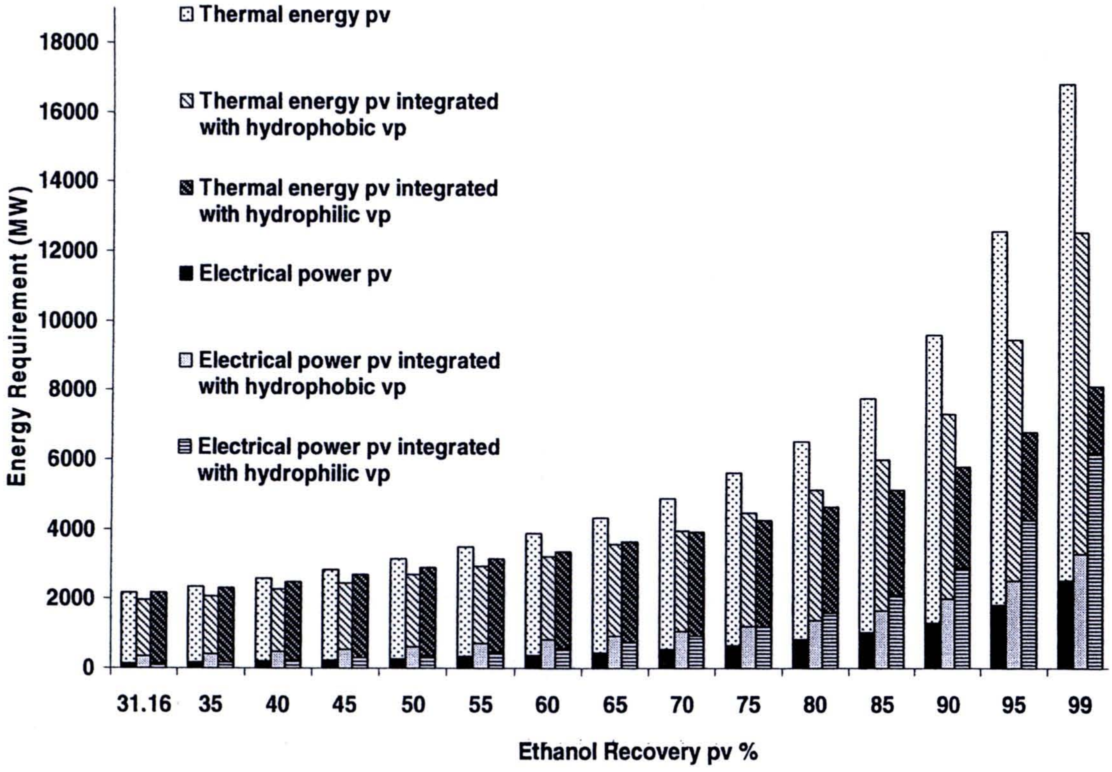


Figure 5.10 Effect of ethanol recovery of PTMSP pervaporation on energy requirement of both types of vapor permeation

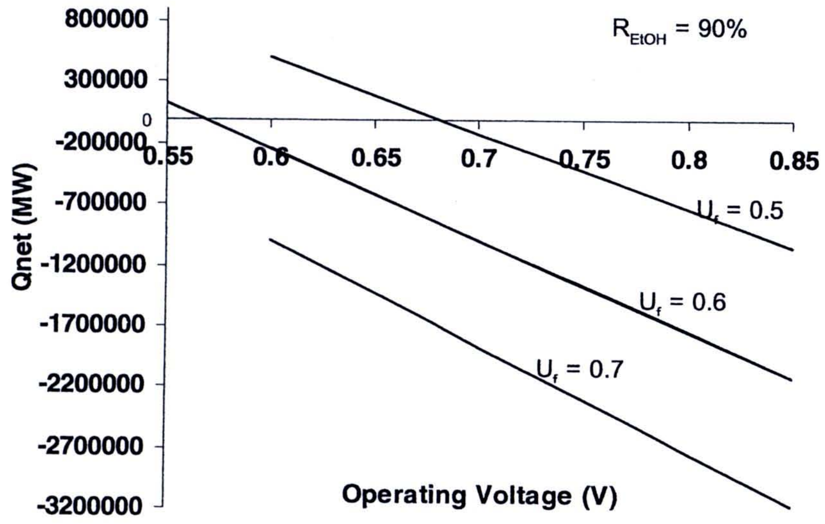
For hydrophobic pervaporation, the demand of thermal energy is the highest compared to the other two cases especially at high ethanol recovery but it requires the lowest electrical power. When the other two cases are considered at the low range of ethanol recovery, an integration with the hydrophilic vapor permeation consumes thermal energy a little higher than in the other case. Nevertheless, when the ethanol recovery is further increased, the demand of thermal energy does not significantly increase and it becomes lower than that of the hydrophobic vapor permeation at 70% ethanol recovery. Although the hydrophilic vapor permeation requires less thermal energy, it consumes higher electrical power.

5.2.3 Performance evaluation of SOFC system under appropriate operating conditions

5.2.3.1 Effects of SOFC operating voltage and fuel utilization on the net thermal energy (Q_{net})

From the above studies, the proposed purification process could offer the desired ethanol concentration at higher ethanol recovery by using integrated pervaporation and vapor permeation. A pervaporation with poor ethanol separation factor recovered a high amount of ethanol but the ethanol concentration was still lower than the desired concentration. Then, the permeate stream was purified by vapor permeation to reach 25 mol% of ethanol. However, an electrical power consumption was required further from a vacuum pump of vapor permeation as shown in Figure 5.10. Therefore, in this section, it is necessary to evaluate the overall performance focusing on the net thermal energy (Q_{net}) obtained from the SOFC systems integrated with the proposed purification process. The effects of fuel utilization (U_f) and operating voltage (V) on Q_{net} are presented in Figures 5.11 and 5.12 for high and low ranges of ethanol recovery for both types of vapor permeation, respectively. At high ethanol recovery, Figure 5.11a) referring to the hydrophobic type shows that there is a narrow range of fuel utilization values which can be operated above $Q_{net}=0$, while Figure 5.11b) referring to the hydrophilic type shows a wider range of fuel utilization values. This means the condition has the remaining heat higher than the other case at the same fuel utilization and operating voltage. At low ethanol recovery, Figures 5.12a) and 5.12b) show slightly different net thermal energy between the hydrophobic and hydrophilic types, indicating that the hydrophilic vapor permeation provides the net thermal energy slightly lower than the hydrophobic vapor permeation. However, this section only investigates the feasibility of operating conditions that can serve $Q_{net} \geq 0$. An electrical efficiency is another important performance indicator of the system to be evaluated further in the next section.

a)



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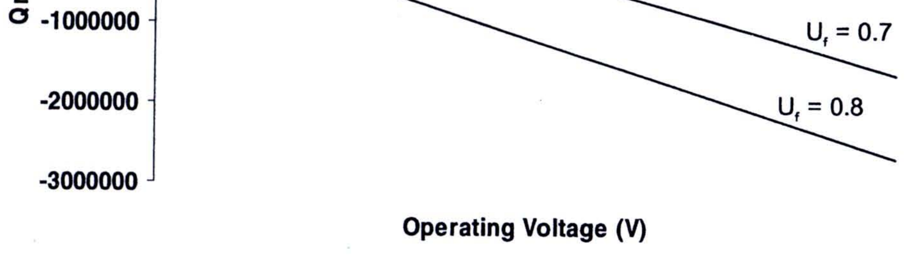

Figure 5.11 Effects of operating voltage and fuel utilization on Q_{net} at high ethanol recovery: a) hydrophobic vapor permeation and b) hydrophilic vapor permeation.

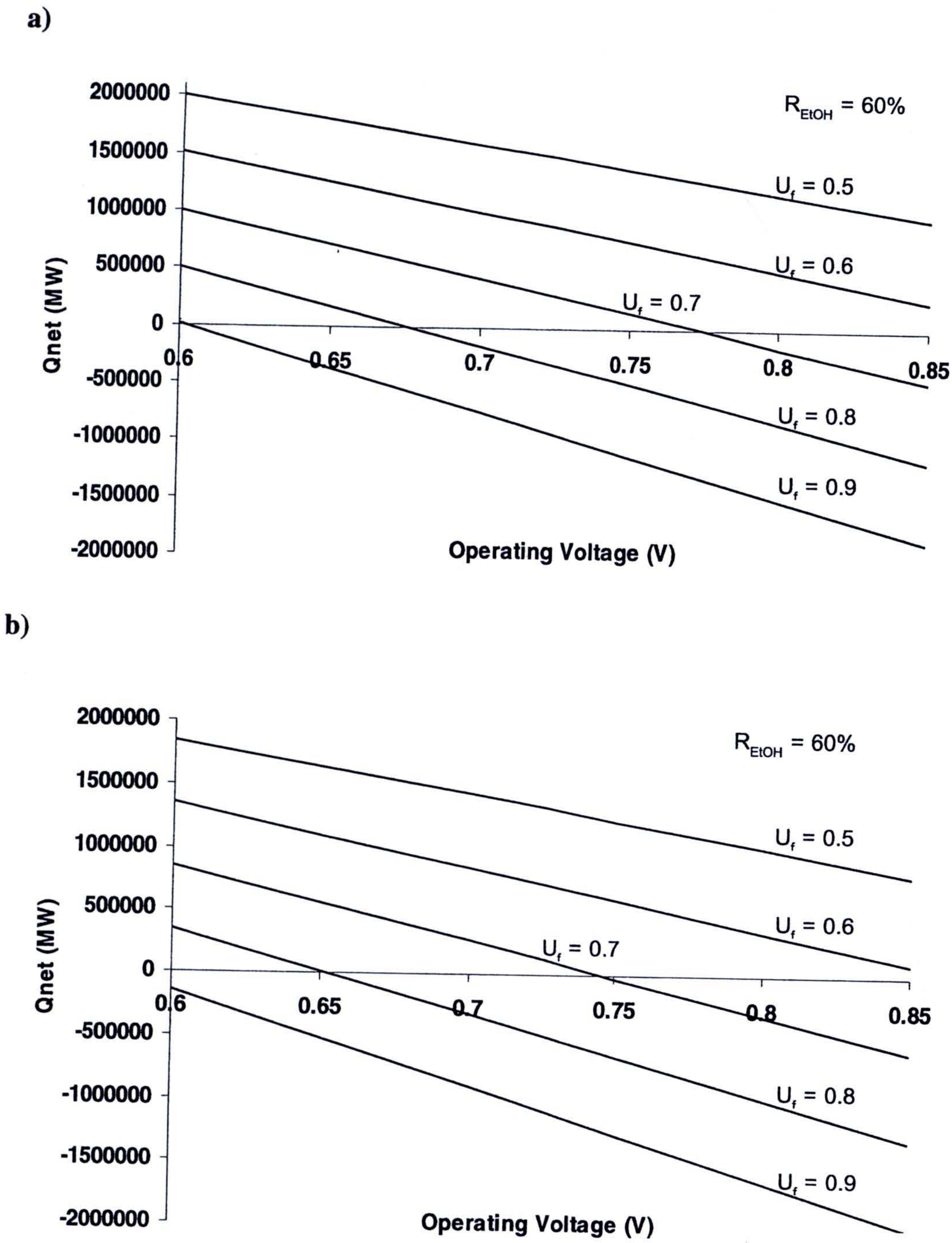

Figure 5.12 Effects of operating voltage and fuel utilization on Q_{net} at low ethanol recovery: a) hydrophobic vapor permeation and b) hydrophilic vapor permeation.

5.2.3.2 Optimal efficiency comparison between SOFC systems with two different membrane types of vapor permeation at the condition of $Q_{net} = 0$

In order to operate the SOFC without demanding additional energy from an external source and to achieve the highest electrical efficiency, the system should be operated at the condition with net thermal energy (Q_{net}) equals to zero. From the previous section, it was feasible to operate an SOFC system with the proposed purification process under this condition. In this section, the electrical efficiency comparison between the SOFC systems with hydrophobic and hydrophilic vapor permeation is studied at various values of pervaporation ethanol recovery to determine a suitable purification system for operation. From Figure 5.13, the results obtained from simulation studies are based on the following operating conditions: Operating voltage = 0.6 V and T_{SOFC} = 1073 K. It should be noted that the SOFC stack can be operated at other values of operating voltage; however, based on the energy self-sufficient condition in this work, the overall electrical efficiency does not vary with the operating voltage. At higher operating voltage, although the SOFC stack efficiency is higher, the lower fuel utilization is required in order to leave sufficient fuel for generating enough heat at the afterburner for use within the system. The overall electrical efficiency gradually increases when increasing the ethanol recovery up to 75%. At higher ethanol recovery, the energy requirement including thermal and electrical energy for purification system rapidly increases as shown in Figure 5.10. Accordingly, the overall electrical efficiency drops dramatically especially in case of the hydrophobic type represented by the dashed line.

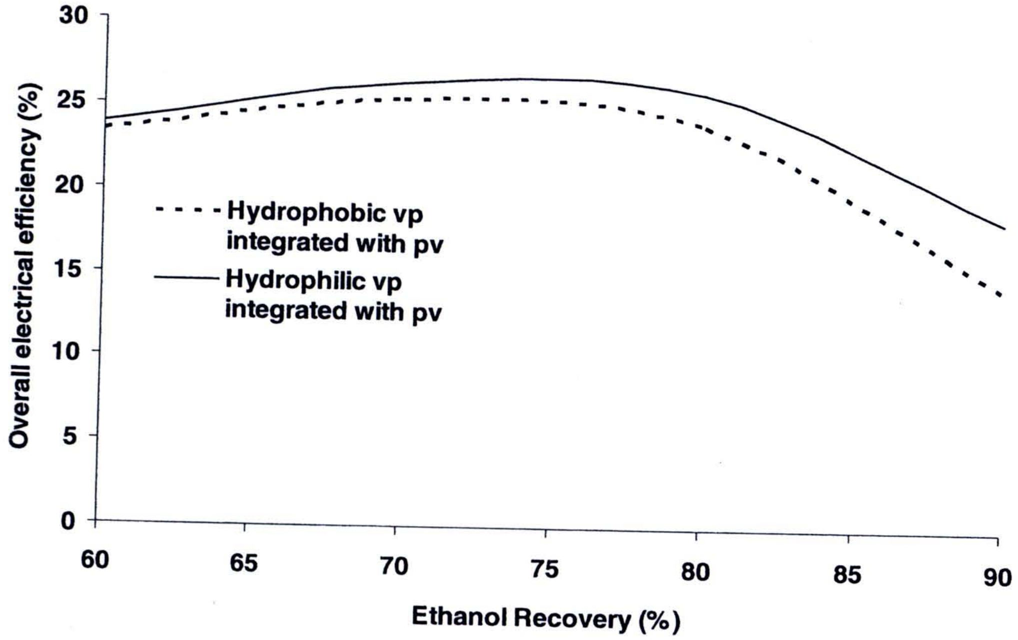

Figure 5.13 Effect of ethanol recovery on the overall electrical efficiency of two different membrane types of vapor permeation.

The system with hydrophobic type offers the overall system efficiency lower than that with the hydrophilic type because its summation of energy consumption including thermal and electrical energy is higher than that of the hydrophilic type especially at high ethanol recovery as illustrated in Figure 5.10. As shown in Figure 5.13, it was found that the optimal overall electrical efficiency obtained from the hydrophilic type was 26.56% at 75% ethanol recovery.

5.2.3.3 Efficiency comparison of SOFC systems before and after installing a vapor permeation unit

After a suitable purification system was obtained from the previous studies, the overall electrical efficiencies for the SOFC systems with and without vapor permeation are compared in this section based on the following operating conditions: Operating voltage = 0.6 V and T_{SOFC} = 1073 K. According to the use of PTMSP pervaporation with $\alpha_{E/W} = 10.7$ as a base case, Table 5.2 shows the results when installing the hydrophilic vapor permeation which was a suitable choice to be installed after the pervaporation. The obtained electrical efficiency is 26.56% compared to 10.96% of the SOFC with a pervaporation alone because it can recover an amount of ethanol at 75% while the base case can only recover ethanol at 31.16% for 25 mol% ethanol concentration. Although an additional vapor permeation requires an electrical power for operating the vacuum pump, it still obtains the net electrical power ($W_{e,net}$) higher than the case with a single pervaporation because of no heat consumption requirement in a separation of vapor permeation as mentioned earlier and the extra electrical power consumption takes only a little effect on the overall efficiency. Therefore, the system does not significantly reduce the fuel utilization values. Moreover, it can be observed that the addition of vapor permeation system has the overall electrical efficiency which can overcome the case of PDMS(ZSM-5 mixed matrix) with $\alpha_{E/W} = 15.5$. Nevertheless, it should require higher ethanol separation factor values of hydrophobic pevaporation for a desired ethanol concentration at high ethanol recovery in order to gain higher overall system efficiency as seen in the case of ZSM-5/α-Al_2O_3 which shows the electrical efficiency of 34.02%.

Table 5.2 Efficiency comparison of SOFC system between with and without extra vapor permeation

Membrane Pervaporation	Ethanol Recovery (%) (25mol%ethanol)	Fuel Utilization (%)	$W_{e,net}$ (MW)	Efficiency (%)
PTMSP ($\alpha_{E/W}$ =10.7)	31.16	67.75	1,765.7	10.96
PTMSP ($\alpha_{E/W}$ = 10.7) with hydrophilic vapor permeation ($\alpha_{W/E}$ = 125.2)	75	86.5	5,392.3	26.56
PDMS(ZSM-5mixed matrix) ($\alpha_{E/W}$ = 15.5)	54	89.2	4,007.5	23.96
ZSM-5/α-Al_2O_3 ($\alpha_{E/W}$ = 24)	71	95.3	5,666.25	34.02

5.3 Performance comparison of SOFC system integrated with different bioethanol purification processes

From the above studies, a hybrid vapor permeation-pervaporation process was proven as an efficient separation performance brought to obtain higher performance of SOFC system following by the results on Table 5.2. To obviously show its performance improvement, the overall electrical efficiency of SOFC system using conventional distillation column and hybrid vapor permeation-pervaporation process should be compared. From Table 5.2, a hydrophobic pervaporation membrane of ZSM-5/α-Al_2O_3 which has the highest separation factor ($\alpha_{E/W}$ = 24) is further developed by sequentially adding a hydrophilic vapor permeation and the results of its system configurations are shown in Figure 5.14. Based on the operating conditions: Operating voltage = 0.75V, T_{SOFC} = 1073K and Permeate pressure = 0.15atm, it can be observed that an increase of ethanol recovery from 71% to 75% shows a significant improvement of the overall electrical efficiency from 34.28% to 45.45%. When increasing the ethanol recovery above 75%, the remaining thermal energy represented by Q_{net} on the right y-axis is released from the system eventhough the fuel cell is operated at almost highest fuel utilization (U_F = 99%) to produce high electricity and reduce the residual fuel for combustion. It can be explained that the extra added vapor permeation required no thermal energy for its separation but consumed some electrical power for operating the vacuum pump, while the amount of ethanol considered as a fuel can be obtained even more. Accordingly, heat and electrical power requirement of the system can be enough supplied by SOFC without relying on the afterburner to combust residual fuel to generate excess heat released to the environment. Since the vacuum pumps of both pervaporation and vapor permeation consume more electrical power followed by increasing ethanol recovery until after 85% ethanol recovery, the overall electrical efficiency then obviously decreases.

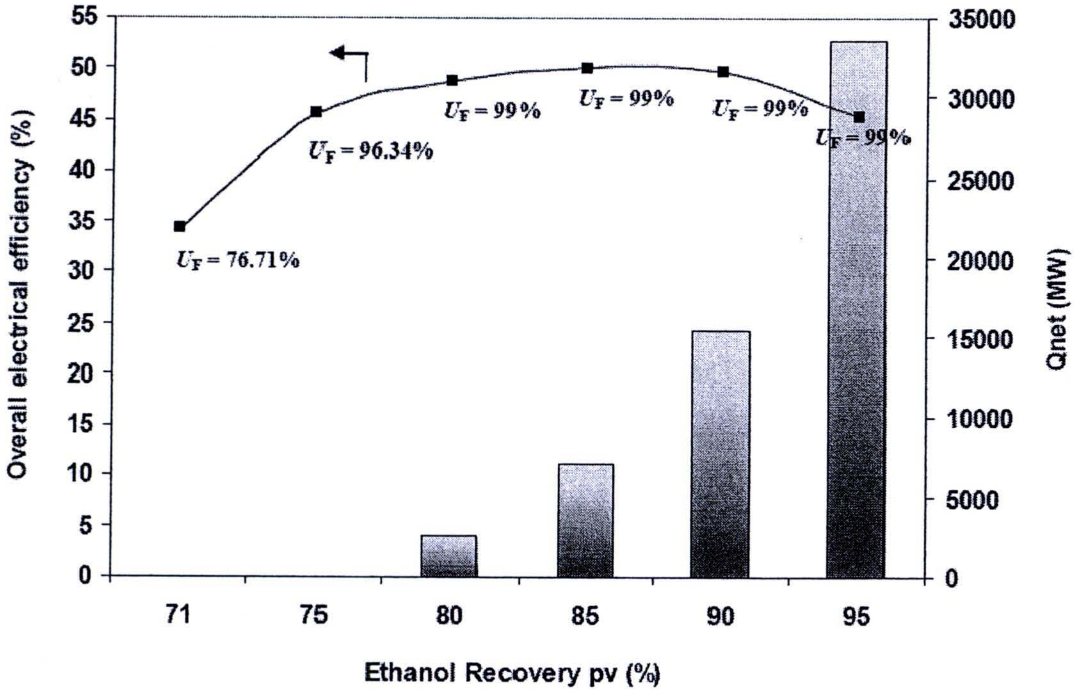

Figure 5.14 Effect of ethanol recovery on the overall electrical efficiency and the net energy (Q_{net}) using hybrid vapor permeation-pervaporation process based on a pervaporation membrane ($\alpha_{E/W}$ = 24).

The separation factor values required for the hydrophilic vapor permeation are presented in Figure 5.15. The values are also compared with the values of separation factor required for hydrophobic pervaporation which provides an equivalent ethanol recovery at 25 mol% ethanol. At 71% ethanol recovery, the results show that this condition requires only a pervaporation with $\alpha_{E/W} = 24.03$ which is available in real membrane as shown in Table 5.1 and not necessary to add a vapor permeation expressed as $\alpha_{W/E} = 1.12$. For a higher ethanol recovery, the obtained separation factor values of hydrophobic pervaporation are too high for its available membrane, while the hydrophilic vapor permeation can be served with real membrane material as in the previous mentioned statement.

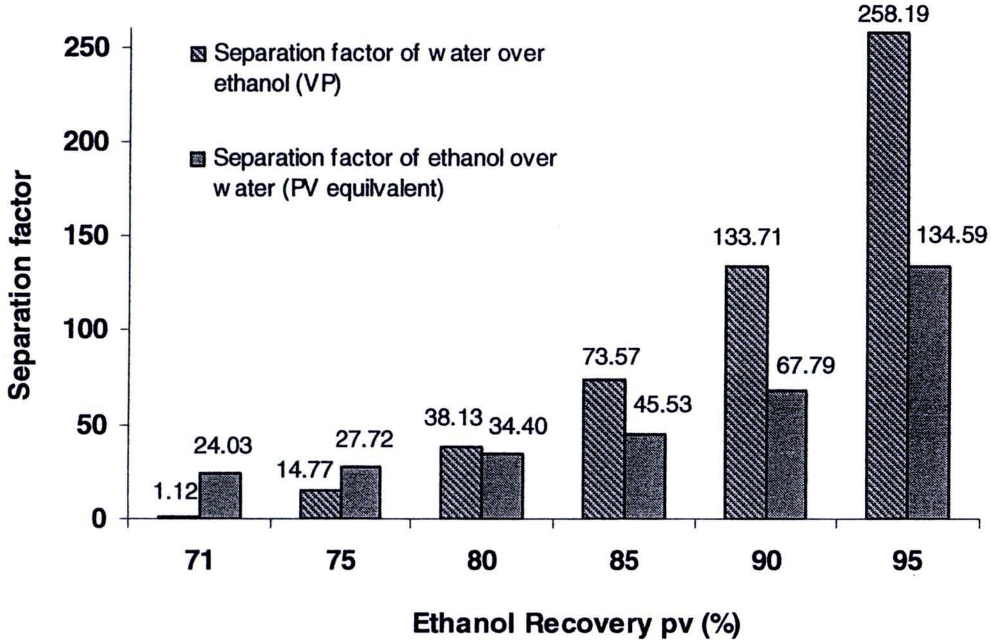

Figure 5.15 A comparison of separation factor between added vapor permeation ($\alpha_{W/E}$) based on pervaporation with $\alpha_{E/W} = 24$ and pervaporation ($\alpha_{E/W}$).

Finally, the performance of SOFC system integrated with various bioethanol purification processes i.e. conventional distillation column, hybrid vapor permeation-pervaporation and only pervaporation are compared as shown in Figure 5.16. Based on the same ethanol recovery (75%), the results indicate that a use of combined hybrid vapor permeation-pervaporation is regarded as having the best performance for SOFC system which can offer the overall electrical efficiency (45.46%) of about 2 times compared with using a distillation column (22.53%). In case of using only a pervaporation, it can be merely obtained the overall electrical efficiency at 36.46% because its overall system requires more thermal energy than the case of hybrid vapor permeation-pervaporation which has a cooler at vapor permeation's permeate stream to recover valuable heat from steam to supply the preheater operated at 1023 K as shown in Figure 5.7b). Then its SOFC unit can utilize fuel at high level (96.35%), resulting in the highest overall performance apart from the case of distillation that its SOFC utilizes less fuel to have enough residual fuel for combustion supplying heat to all heat-demanding units especially the reboiler. However, the power density of hybrid vapor permeation-pervaporation is lower than the other two cases because larger SOFC area is required to operate at high fuel utilization.

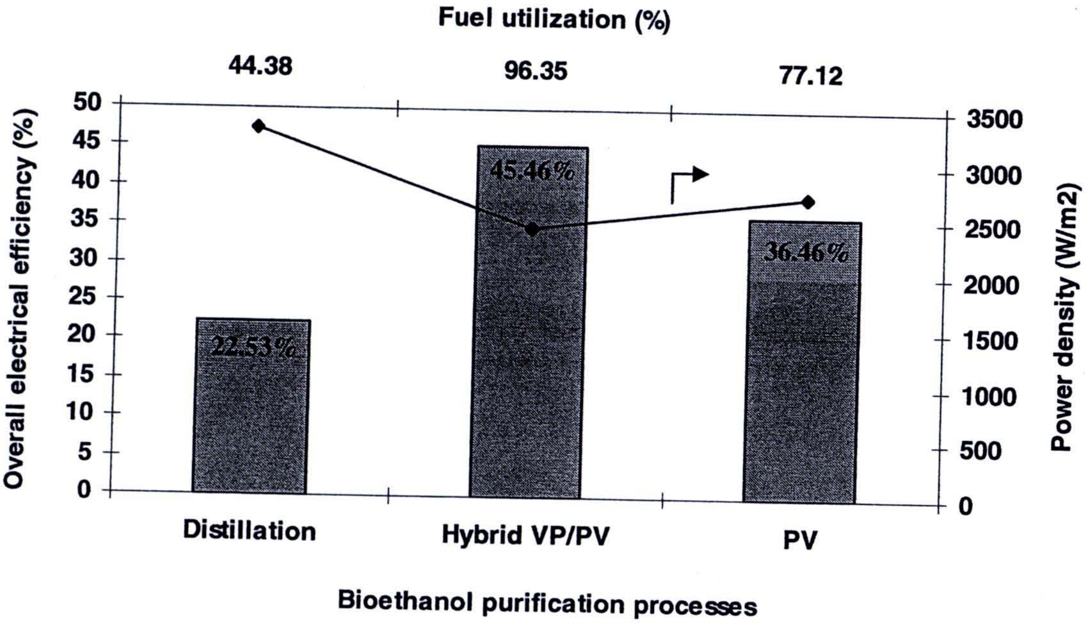

Figure 5.16 Performance comparison of SOFC system integrated with different bioethanol purification processes based on $Q_{net} = 0$ ($R_{EtOH} = 75\%$, $V = 0.75V$, $T_{SOFC} = 1073K$, $P_p = 0.15atm$).