ELECTEROCHEMICAL STUDY OF SOLFONATED POLY ETHER ETHER KETONE NANOCOMPOSITE MEMBRANE AT MODERATE TEMPERATURE FOR DIRECT METHANOL FUEL CELL APPLICATION

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ABSTRACT

High methanol permeability and expensive price of current commercial Nafion® membrane for direct methanol fuel cell (DMFC) have encouraged researchers to modify proton exchange membrane (PEM). Sulfonted poly ether ether ketone (SPEEK) is a polymer which attracted a lot of attention recently. This study aimed to test the DMFC performance of nanocomposite SPEEK membrane filled with Cloisite 15A® clay by introducing 2,4,6 triaminopyrimidine (TAP) as a compatibilizer as electrolyte membrane at room temperature to 80^{o}C and compare with Nafion 117. SPEEK polymer was made at 60^{o}C in order to obtain the degree of sulfonation of 60%. According to the results, the SPEEK nanocomposite with the following composition SP60/CL2.5/TAP5.0 showed higher proton conductivity and methanol permeability than of Nafion 117 at various temperatures because of the presence of CL and TAP addition.Furthemore the highest overall performance(membrane selectivity) was allocated to the SP60/CL2.5/TAP5.0 at 60^{o}C while the lowest one was for Nafion 117 at 80^{o}C. In addition DMFC performance results showed the OCV for the nanocomposite membrane increase when the temperature increase. In addition voltage and power density increase with temperature incerement due to catalyst high activity on electrode surface,and higher proton conductivity , clearly the maximum power density at 60^{o}C was 54.93 (mWcm^{-2}).

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INTRODUCTION

1.1 Research Background

Fuel cells are the devices that produce electricity from chemical energy with high efficiency and low pollutant. During the recent decades fuel cells have been magnetized high interest because of high-energy request, fossil fuel shortage, and environmental treatments (Liu *et al.*, 2006). In general, fuel cells are known as “alternative battery” as they have some similarity to batteries but do not follow the thermodynamic Carnot cycle energy conversion due to their different mechanism. Their pollutions are very lower than most of the environmental standards (Othman, 2009).

Different types of fuel cell are recognized by the electrolyte material. This clarifies: 1) kind of chemical reactions occur inside the cell, 2) kind of catalyst needed, 3) the temperature range of operation, 4) types of fuels used and other factors. Table 1.1 shows several types of fuel cells being used (Othman, 2009).

Table 1. 1 Types of fuel cells

Type	**Electrolyte**	**Fuel/ Oxidant**	**Operating Temperature (°C)**	**Application**
Molten Carbonate (MCFC)	Carbonate Salt (Lithium & Potassium Carbonate Mixture)	H_2/O_2	~ 650	Stationary
Phosphoric Acid (PAFC)	Pottasium hydroxide solution	H_2/O_2	~ 220	Stationary
Solid Oxide (SAFC)	Solid Ceramic	H_2/O_2	~ 1000	Vehicle Stationary
Alkaline (AFC)	Potassium Hydroxide Solution	H_2/O_2	60-120	Vehicle Spatial
Polymer Electrolyte (PEMFC)	Solid Ion Exchange Membrane	H_2/O_2	50-100	Vehicle Stationary Portable Power
Direct Methanol (DMFC)	Solid Ion Exchange Membrane	CH_3OH/O_2	50-120	Vehicle Portable Power

Proton exchange membrane (PEM) fuel cells or polymer electrolyte membrane fuel cells have magnetized more attention amongst different types of fuel cells during recent decade, due to their excellent performance in stationary and portable devices. These types of fuel cells applied solid polymer membranes as the electrolyte. The advantages of PEM can be listed as follows: 1) absence of corrosive liquid reduces corrosion; 2) Operation in low temperature let prepare instant response to any alter in power demand and 3) Can produce high power densities with lower weight, cost and compact (Libby *et al.*, 2003).

Basically there are two types of PEM fuel cells, including the hydrogen PEM fuel cell and direct methanol fuel cell (DMFC), both are excellent for substituting the electricity generators (Othman, 2009). Hydrogen PEMFC mainly applied in automotive and residential applications; however DMFCs are more suitable for portable electronic devices because of their low cost, low temperature and pressure operation, rapid refueling and compact cell design (Ge and Liu, 2005). Generally, there are two main problems when employing DMFC: 1) slow oxidation kinetics of the fuel 2) methanol crossover through membrane that due to depolarization of the cell, decrease fuel efficiency and reduction in OCV (open circuit voltage) (Hasani-Sadrabadi *et al.*, 2010).

Therefore recent researches concentrate on the modification of membranes to achieve more proton conductivity at higher temperatures, prepare a sufficient water supply and decrease methanol crossover rate. During former decade, Scientists produced novel polymers with non-fluorinated backbones, and introducing different types of inorganic fillers into polymeric matrices, including montmorillonite, titanium dioxide, zirconium phosphate silica and zeolites (Hasani-Sadrabadi, *et al.*, 2010). The latter system is known as polymer nanocomposites.

Polymer nanocomposites can be categorized into hybrid systems consisting of high surface are a nanostructure components. The exclusive properties of polymer- clay nanocomposites come from nanoscale spreading of clay layers into the polymeric matrix, which robustly depends on interfacial characteristics. Amongst non-fluorinated hydrocarbons, poly ether ether ketone (PEEK), was presented to be sufficient for fuel cells, due to its cheaper price, better film developing properties, and good thermal, mechanical and chemical resistance (Hasani-Sadrabadi, *et al.*, 2010).

1.2 Problem Statement

There are two main problems normally encountered during the applications of direct methanol fuel cells (Gaowen and Zhentao, 2005): first is the slow oxidation rate of methanol and secondly the excessive methanol permeation through the membranes. Nafion® (Dupont), Flemion® (Asahi Glass Company), Aciplex® (Asahi Chem.) perfluorinated ionomer (PFI) membranes are usually developed as electrolytes, due to their good resistance during cell operation and high proton conductivity. On the other hand the methanol cross over is still high in these types of membranes that undesirable for DMFC performance (Norddin *et al.*, 2009).

Since recent decade, a number of researchers had attempted to solve PFI's weaknesses. There were three main techniques employed to minimize the weakness of PFI's: 1) development of PFI membranes, 2) modification of other fluoropolymer membranes, and 3) improvement of non- fluorinated polymer membranes (Jaafar *et al.*, 2009).

Because of the high proton conductivity of non- fluorinated polymers, several attempts have been done to develop the membrane performance by reducing methanol crossover through the membrane and even enhanced proton conductivity for DMFC application, by applying inorganic materials such as clay. Amongst natural clays, smectites, which are family of either montmorillonite (MMT) or hectorites, are a suitable material for DMFC application because of their excellent proton conductivity, proper surface area, high surface reactivity, and low methanol permeability (Kathleen, 2000) .

Although the MMT has advantages, but there are still some weaknesses of MMT because of its chemical microstructure properties. Due to hydrophilic properties of silicate clays and low attraction for hydrophobic polymers, an organic development on the clay surface must be done in order to improve their compatibility with polymeric materials (Lin *et al.*, 2007).

The adjustment of inorganic clays to organoclays is the popular method to modify the compatibility properties of MMT clay. Cloisite15A® is one of the developed MMT clays that has desirable advantages such as high interlayer distance (~31.5 A) and high aspect ratio (70- 150), which is donate to good proton conductivity and also low methanol crossover (Jaafar *et al.*, 2011).

Jaafar et al. (2011) presented the SP63/2.5Cl/5.0TAP polymer-clay nanocomposites membrane as a substitute proton exchange membrane (PEM) for DMFCs with better DMFC performance than Nafion® 112. It has been reported that the new membrane has high proton conductivity (16.3×10^{-4} $mScm^{-1}$), low methanol permeability (1.3×10^{-1} cm^2 s^{-1}) and also high mechanical stability at room temperature and 100%RH (Jaafar, *et al.*, 2011). To the best of our knowledge, the performance of mentioned membrane at different operating parameters such as temperature, has never been studied before.

1.3 Research Objective

Based on the background of the study and the problem statement addressed, therefore the objectives of this study is to study the performance of SP63/2.5Cl/5.0TAP membrane in direct methanol fuel cell at different operating temperatures.

1.4 Research Scope

In order to achieve the above objectives, the following scopes of work have been drawn:

i. Preparing the SP60/2.5 Cl/ 5.0 TAP proton exchange membrane.

ii. Measuring the, methanol permeability of SPEEK nanocomposite membrane and Nafion 117 at the temperature range of room temperature to 80^{o}C.

iii. Measuring the proton conductivity of SPEEK nanocomposite membrane and Nafion 117, at the temperature range of room temperature to 80^{o}C.

iv. Preparing the Membrane Electrode Assembly (MEA) from the SP60/2.5 Cl/ 5.0 TAP membrane

v. Studying the performance of SP60/2.5 Cl/ 5.0 TAP membrane in DMFC single cell in terms of voltage and power density at different temperatures

REFERENCES

APPLEBY, A. J. F., R. L. (1998). *FUEL CELL HANDBOOK*. NEW YORK: VAN NOSTRAND REINHOLD.

BAE, B., KHO, B. K., LIM, T.-H., OH, I.-H., HONG, S.-A. AND HA, H. Y. (2006). PERFORMANCE EVALUATION OF PASSIVE DMFC SINGLE CELLS. *JOURNAL OF POWER SOURCES*, 158(2), 1256-1261. DOI: 10.1016/J.JPOWSOUR.2005.10.024

BALAZS, A. C., EMRICK, T. AND RUSSELL, T. P. (2006). NANOPARTICLE POLYMER COMPOSITES: WHERE TWO SMALL WORLDS MEET. *SCIENCE*, 314(5802), 1107-1110. DOI: 10.1126/SCIENCE.1130557

CHEN. (2003). *FUEL CELL TECHNOLOGY HANDBOOK*: BOCA RATON LONDON

NEW YORK WASHINGTON.

CHEN, S., YE, F. AND LIN, W. (2010). EFFECT OF OPERATING CONDITIONS ON THE PERFORMANCE OF A DIRECT METHANOL FUEL CELL WITH PTRUMO/CNTS AS ANODE CATALYST. *INTERNATIONAL JOURNAL OF HYDROGEN ENERGY*, 35(15), 8225-8233. DOI: 10.1016/J.IJHYDENE.2009.12.085

CHEN, Y. AND IROH, J. O. (1999). SYNTHESIS AND CHARACTERIZATION OF POLYIMIDE/SILICA HYBRID COMPOSITES. *CHEMISTRY OF MATERIALS*, 11(5), 1218-1222. DOI: 10.1021/CM980428L

DECHER, G. (1997). FUZZY NANOASSEMBLIES: TOWARD LAYERED POLYMERIC MULTICOMPOSITES. *SCIENCE*, 277(5330), 1232-1237.

DI VONA, M. L., AHMED, Z., BELLITTO, S., LENCI, A., TRAVERSA, E. AND LICOCCIA, S. (2007). SPEEK-TIO2 NANOCOMPOSITE HYBRID PROTON CONDUCTIVE MEMBRANES VIA IN SITU MIXED SOL–GEL PROCESS. *JOURNAL* of Membrane Science, 296(1-2), 156-161. doi: 10.1016/j.memsci.2007.03.037

Escribano, S., Blachot, J.-F., Ethève, J., Morin, A. and Mosdale, R. (2006). Characterization of PEMFCs gas diffusion layers properties. *Journal of Power Sources*, 156(1), 8-13. doi: 10.1016/j.jpowsour.2005.08.013

Gao, Y., Robertson, G. P., Guiver, M. D., Jian, X., Mikhailenko, S. D., Wang, K., et al. (2003). Sulfonation of poly(phthalazinones) with fuming sulfuric acid mixtures for proton exchange membrane materials. *Journal of Membrane Science*, 227(1–2), 39-50. doi: 10.1016/j.memsci.2003.08.020

Gao, Y., Sun, G. Q., Wang, S. L. and Zhu, S. (2010). Carbon nanotubes based gas diffusion layers in direct methanol fuel cells. *Energy*, 35(3), 1455-1459. doi: 10.1016/j.energy.2009.11.031

Gaowen, Z. and Zhentao, Z. (2005). Organic/inorganic composite membranes for application in DMFC. *Journal of Membrane Science*, 261(1–2), 107-113. doi: 10.1016/j.memsci.2005.03.036

Ge, J. and Liu, H. (2005). Experimental studies of a direct methanol fuel cell. *Journal of Power Sources*, 142(1-2), 56-69. doi: 10.1016/j.jpowsour.2004.11.022

Gosalawit, R., Chirachanchai, S., Shishatskiy, S. and Nunes, S. P. (2008). Sulfonated montmorillonite/sulfonated poly(ether ether ketone) (SMMT/SPEEK) nanocomposite membrane for direct methanol fuel cells (DMFCs). *Journal of Membrane Science*, 323(2), 337-346. doi: 10.1016/j.memsci.2008.06.038

Hasani-Sadrabadi, M. M., Dashtimoghadam, E., Sarikhani, K., Majedi, F. S. and Khanbabaei, G. (2010). Electrochemical investigation of sulfonated poly(ether ether ketone)/clay nanocomposite membranes for moderate temperature fuel cell applications. *Journal of Power Sources*, 195(9), 2450-2456. doi: 10.1016/j.jpowsour.2009.11.090

Hickner, M. A. (2003). *Transport and Structure in Fuel Cell Proton Exchange Membranes.* PhD, Virginia Polytechnic Institute.

Jaafar. (2006). *Developement and charctrization of sulfonated poly ethet ether ketone mambrane for direct methanol fuel cell application.* Master, Universiti Teknologi Malaysia.

Jaafar, Ismail, A. F. and Matsuura, T. (2009). Preparation and barrier properties of SPEEK/Cloisite 15A®/TAP nanocomposite membrane for DMFC application. *Journal of Membrane Science*, 345(1-2), 119-127. doi: 10.1016/j.memsci.2009.08.035

Jaafar, Ismail, A. F., Matsuura, T. and Nagai, K. (2011). Performance of SPEEK based polymer–nanoclay inorganic membrane for DMFC. *Journal of Membrane Science*, 382(1-2), 202-211. doi: 10.1016/j.memsci.2011.08.016

Jaafar, J. (2011). *Development of sulfonated poly (ether ether ketone) triaminopyrimidine nanocomposite membrane dor direct methanol fuel cell*. PhD, Universiti teknologi malaysia, skudai.

Jaafar, J., Ismail, A. F., Matsuura, T. and Nagai, K. (2011). Performance of SPEEK based polymer–nanoclay inorganic membrane for DMFC. *Journal of Membrane Science*, 382(1-2), 202-211. doi: 10.1016/j.memsci.2011.08.016

Jiang, R., Kunz, H. R. and Fenton, J. M. (2005). Investigation of membrane property and fuel cell behavior with sulfonated poly(ether ether ketone) electrolyte: Temperature and relative humidity effects. *Journal of Power Sources*, 150(0), 120-128. doi: 10.1016/j.jpowsour.2005.03.180

Kathleen, C. (2000). Synthetic organo- and polymer–clays: preparation, characterization, and materials applications. *Applied Clay Science*, 17(1-2), 1-23. doi: 10.1016/s0169-1317(00)00005-3

Khulbe, K. C., Feng, C. Y. and Matsuura, T. (2008). Synthetic Membranes for Membrane Processes

Synthetic Polymeric Membranes (pp. 5-18): Springer Berlin Heidelberg.

Kim, T. K., Kang, M., Choi, Y. S., Kim, H. K., Lee, W., Chang, H., et al. (2007). Preparation of Nafion-sulfonated clay nanocomposite membrane for direct menthol fuel cells via a film coating process. *Journal of Power Sources*, 165(1), 1-8. doi: 10.1016/j.jpowsour.2006.11.055

Li, Q., He, R., Jensen, J. O. and Bjerrum, N. J. (2003). Approaches and Recent Development of Polymer Electrolyte Membranes for Fuel Cells Operating above 100 °C. *Chemistry of Materials*, 15(26), 4896-4915. doi: 10.1021/cm0310519

Libby, B., Smyrl, W. H. and Cussler, E. L. (2003). Polymer-zeolite composite membranes for direct methanol fuel cells. *AIChE Journal*, 49(4), 991-1001. doi: 10.1002/aic.690490416

Lin, Y.-F., Yen, C.-Y., Hung, C.-H., Hsiao, Y.-H. and Ma, C.-C. M. (2007). A novel composite membranes based on sulfonated montmorillonite modified Nafion® for DMFCs. *Journal of Power Sources*, 168(1), 162-166. doi: 10.1016/j.jpowsour.2007.02.079

Liu, Song, C., Zhang, L., Zhang, J., Wang, H. and Wilkinson, D. P. (2006). A review of anode catalysis in the direct methanol fuel cell. *Journal of Power Sources*, 155(2), 95-110. doi: 10.1016/j.jpowsour.2006.01.030

Mayahi, A. (2012). *Temperature effect on sulfonatedpoly(etheretherkethone) with charge surface modifying*

MACROMOLECULE FOR DIRECT METHANOL FUEL CELL APPLICATION. MASTER, UNIVERSITI TEKNOLOGI MALAYSIA, JOHOR.

MCNICOL, B. D., RAND, D. A. J. AND WILLIAMS, K. R. (1999). DIRECT METHANOL–AIR FUEL CELLS FOR ROAD TRANSPORTATION. *JOURNAL OF POWER SOURCES*, 83(1-2), 15-31. DOI: 10.1016/S0378-7753(99)00244-X

MIKHAILENKO, S. D., ZAIDI, S. M. J. AND KALIAGUINE, S. (2001). SULFONATED POLYETHER ETHER KETONE BASED COMPOSITE POLYMER ELECTROLYTE MEMBRANES. *CATALYSIS TODAY*, 67(1–3), 225-236. DOI: 10.1016/S0920-5861(01)00290-5

MIKKOLA, M. (2001). *EXPERIMENTAL STUDIED ON POLYMER ELECTROLYTE MEMBRANE FUEL CELL STACKS*. PHD, HELSINKI UNIVERSITY OF TECHNOLOGY.

NORDDIN, M. N. A. M., ISMAIL, A. F., RANA, D., MATSUURA, T. AND TABE, S. (2009). THE EFFECT OF BLENDING SULFONATED POLY(ETHER ETHER KETONE) WITH VARIOUS CHARGED SURFACE MODIFYING MACROMOLECULES ON PROTON EXCHANGE MEMBRANE PERFORMANCE. *JOURNAL OF MEMBRANE SCIENCE*, 328(1-2), 148-155. DOI: 10.1016/J.MEMSCI.2008.12.009

NUNES, S. P., RUFFMANN, B., RIKOWSKI, E., VETTER, S. AND RICHAU, K. (2002). INORGANIC MODIFICATION OF PROTON CONDUCTIVE POLYMER MEMBRANES FOR DIRECT METHANOL FUEL CELLS. *JOURNAL OF MEMBRANE SCIENCE*, 203(1-2), 215-225. DOI: 10.1016/S0376-7388(02)00009-1

OEDEGAARD, A., HEBLING, C., SCHMITZ, A., MØLLER-HOLST, S. AND TUNOLD, R. (2004). INFLUENCE OF DIFFUSION LAYER PROPERTIES ON LOW TEMPERATURE DMFC. *JOURNAL OF POWER SOURCES*, 127(1-2), 187-196.

OTHMAN, N. H. B. (2009). *SYNTHESIS, CHARACTERIZATION AND OPTIMIZATION OF SULFONATED*

POLYETHER ETHER KETONE COMPOSITE MEMBRANE FOR DIRECT

METHANOL FUEL CELL. MASTER DEGREE, UNIVERSIT I TEKNOLOGI MALAYSIA SKUDAI.

PASSALACQUA, E., SQUADRITO, G., LUFRANO, F., PATTI, A. AND GIORGI, L. (2001). EFFECTS OF THE DIFFUSION LAYER CHARACTERISTICS ON THE PERFORMANCE OF POLYMER ELECTROLYTE FUEL CELL ELECTRODES. *JOURNAL OF APPLIED ELECTROCHEMISTRY*, 31(4), 449-454.

PEIGHAMBARDOUST, S. J., ROWSHANZAMIR, S. AND AMJADI, M. (2010). REVIEW OF THE PROTON EXCHANGE MEMBRANES FOR FUEL CELL APPLICATIONS. *INTERNATIONAL JOURNAL OF HYDROGEN ENERGY*, 35(17), 9349-9384. DOI: 10.1016/J.IJHYDENE.2010.05.017

ROELOFS, K. S., HIRTH, T. AND SCHIESTEL, T. (2010). SULFONATED POLY(ETHER ETHER KETONE)-BASED SILICA NANOCOMPOSITE MEMBRANES FOR DIRECT ETHANOL FUEL CELLS. *JOURNAL OF MEMBRANE SCIENCE*, 346(1), 215-226. DOI: 10.1016/J.MEMSCI.2009.09.041

SADIQ, A. M. (2000). DESIGN AND FABRICATION OF A

DIRECT METHANOL PROTON EXCHANGE MEMBRANE

FUEL CEIL AND TEST STATION. [THESIS

]. *ROYAL MILITARY COLLEGE OF CANADA*, 141.

SAVADOGO, O. (1998). CHEMINFORM ABSTRACT: EMERGING MEMBRANES FOR ELECTROCHEMICAL SYSTEMS: (I) SOLID POLYMER ELECTROLYTE MEMBRANES FOR FUEL CELL SYSTEMS. *CHEMINFORM*, 29(47), NO-NO. DOI: 10.1002/CHIN.199847334

SILVA, V. S., RUFFMANN, B., VETTER, S., MENDES, A., MADEIRA, L. M. AND NUNES, S. P. (2005). CHARACTERIZATION AND APPLICATION OF COMPOSITE MEMBRANES IN DMFC. *CATALYSIS TODAY*, 104(2-4), 205-212. DOI: 10.1016/J.CATTOD.2005.03.051

Silva, V. S., Weisshaar, S., Reissner, R., Ruffmann, B., Vetter, S., Mendes, A., et al. (2005). Performance and efficiency of a DMFC using non-fluorinated composite membranes operating at low/medium temperatures. *Journal of Power Sources*, 145(2), 485-494. doi: 10.1016/j.jpowsour.2004.12.061

Smitha, B., Sridhar, S. and Khan, A. A. (2005). Proton conducting composite membranes from polysulfone and heteropolyacid for fuel cell applications. *Journal of Polymer Science Part B: Polymer Physics*, 43(12), 1538-1547. doi: 10.1002/polb.20450

Thepkaew, J., Therdthianwong, A. and Therdthianwong, S. (2008). Key parameters of active layers affecting proton exchange membrane (PEM) fuel cell performance. *Energy*, 33(12), 1794-1800. doi: 10.1016/j.energy.2008.08.008

thomas, S., Zalbowitz, M. and Dennis, G. (2000). <Fuel Cells-Green Power.pdf>.

Tripathi, B. P. and Shahi, V. K. (2007). SPEEK–zirconium hydrogen phosphate composite membranes with low methanol permeability prepared by electro-migration and in situ precipitation. *Journal of Colloid and Interface Science*, 316(2), 612-621. doi: 10.1016/j.jcis.2007.08.038

Tripathi, B. P. and Shahi, V. K. (2011). Organic–inorganic nanocomposite polymer electrolyte membranes for fuel cell applications. *Progress in Polymer Science*, 36(7), 945-979. doi: 10.1016/j.progpolymsci.2010.12.005

Wang, M. and Dong, S. (2007). Enhanced electrochemical properties of nanocomposite polymer electrolyte based on copolymer with exfoliated clays. *Journal of Power Sources*, 170(2), 425-432. doi: 10.1016/j.jpowsour.2007.04.031

WANG, Y., CHEN, K. S., MISHLER, J., CHO, S. C. AND ADROHER, X. C. (2011). A REVIEW OF POLYMER ELECTROLYTE MEMBRANE FUEL CELLS: TECHNOLOGY, APPLICATIONS, AND NEEDS ON FUNDAMENTAL RESEARCH. *APPLIED ENERGY*, 88(4), 981-1007. DOI: 10.1016/J.APENERGY.2010.09.030

ZAIDI, S. M. J. AND AHMAD, M. I. (2006). NOVEL SPEEK/HETEROPOLYACIDS LOADED MCM-41 COMPOSITE MEMBRANES FOR FUEL CELL APPLICATIONS. *JOURNAL OF MEMBRANE SCIENCE*, 279(1-2), 548-557. DOI: 10.1016/J.MEMSCI.2005.12.048

ZHANG, YIN, G., WANG, Z. AND SHAO, Y. (2006). EFFECTS OF MEA PREPARATION ON THE PERFORMANCE OF A DIRECT METHANOL FUEL CELL. *JOURNAL OF POWER SOURCES*, 160(2), 1035-1040. DOI: 10.1016/J.JPOWSOUR.2006.02.059

ZHANG, H., LI, X., ZHAO, C., FU, T., SHI, Y. AND NA, H. (2008). COMPOSITE MEMBRANES BASED ON HIGHLY SULFONATED PEEK AND PBI: MORPHOLOGY CHARACTERISTICS AND PERFORMANCE. *JOURNAL OF MEMBRANE SCIENCE*, 308(1-2), 66-74. DOI: 10.1016/J.MEMSCI.2007.09.045